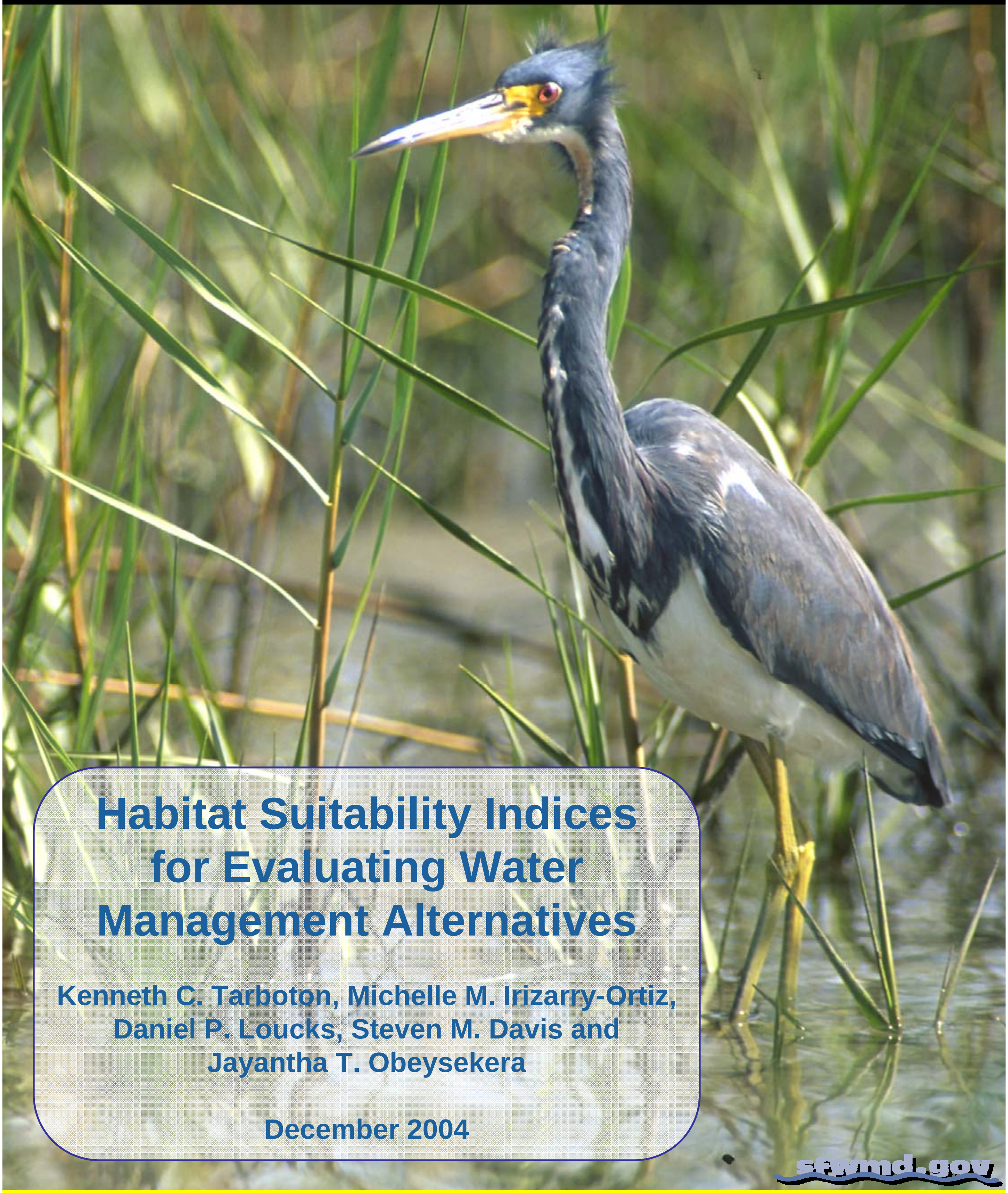
SOUTH FLORIDA WATER MANAGEMENT DISTRICT



Habitat Suitability Indices for Evaluating Water Management Alternatives

Kenneth C. Tarboton, Michelle M. Irizarry-Ortiz, Daniel P. Loucks, Steven M. Davis and Jayantha T. Obeysekera

December 2004

Office of Modeling Technical Report

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**South Florida Water Management District
3301 Gun Club Road
West Palm Beach, Florida 33306
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Preface

This report documents the results of a project undertaken by a number of hydrologists, engineers, and ecologists in the early part of 2001. The project was planned, organized, and implemented in a period of about 4 months as an exercise to see if it might be possible to compare alternative water management policies based on at least the relative impact on ecosystem habitat. The motivation was to be able to address questions related to 'getting the water right.' Just what is right, and what if we can not get the water quite right? Just how sensitive is the condition of the ecosystem to hydrologic targets or goals? In the absence of more detailed ecosystem models available for use by managers, could a simple habitat suitability index based model serve the decisionmaking process?

Habitat suitability index models were developed to use simulated output from the South Florida Water Management Model (SFWMM) and the Natural System Model (NSM). Where possible, the habitat suitability models were calibrated using field observations and expert ecological knowledge. The results were presented at the National Research Council's (NRC) Committee on the Restoration of the Greater Everglades Ecosystem (CROGEE) meeting in April 2001 to an audience that included members of the Governing Board and staff of the South Florida Water Management District (SFWMD) together with representatives from the United States Army Corps of Engineers (USACE), the National Park Service (NPS), and other agencies. Based on responses from that presentation and others, as well as the growing needs of various Restoration Coordination and Verification (RECOVER) teams (http://www.evergladesplan.org/pm/recover/recover_teams.cfm) the postprocessing of hydrologic output data from SFWMM and NSM now include the habitat suitability index features described in this report. Habitat suitability index performance measures for recent Comprehensive Everglades Restoration Plan (CERP) system-wide modeling simulations can be viewed on the CERP System-wide Modeling web site at http://modeling.cerpzone.org/cerp_recover/pmviewer/pmviewer.jsp.

The aim of this work was to develop a transparent, inexpensive, easily understandable, and modifiable way to quantify the links between water management and ecosystem response defined in cause-and-effect conceptual ecological models. Its purpose was to obtain preliminary answers to questions involving trade-offs between water management or restoration plans and costs and ecological habitat impacts. If judged useful, the approach may be applied to more species and more regions of the Everglades ecosystem. But even with improvements that will surely occur, it is important to recognize the limitations of this modeling approach, and to continue the work undertaken to develop ecological individual- and population-based models to improve our understanding of the interactions of various species and their habitats within the ecosystem of the Everglades.

The work presented herein is primarily to illustrate the method of generating habitat suitaiblity index functions. The actual habitat suitability index functions that will be used for evaluation purposes are expected to be updated as our understanding of the system and interactions between habitats increases.

Acknowledgements

This exercise in developing and implementing habitat suitability indicators involved many individuals from many organizations, each volunteering his or her time and knowledge. Developing the methods presented in this report required the expertise of ecologists who are both knowledgeable in their particular subject areas and who are also willing to participate in this admittedly simple approach to modeling a system that they know is much more complex and not very well understood. This particular exercise was considerably aided by the participation of individuals who were at the same time developing more complex landscape and ecosystem models or were themselves involved in other modeling application projects. They did this on their own time (some even while on vacation) and without any budget, over a period of about 4 months. For this we are very grateful. Scientists and engineers from several agencies participated in developing the habitat suitability index functions, programming them and later automating them to be produced as part of the South Florida Water Management Model (SFWMM) postprocessing. Contributors are listed either as authors on each of the main habitat suitability index chapters, or in the list below:

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The first draft of this document underwent review between December 2003 and June 2004. Many excellent comments were received from United States Fish and Wildlife Service staff, including Lorraine Heisler, Callie McMunigal, David Hallac, Tim Pinion, Sandra Sneckenberger, and Heather McSharry, and South Florida Water Management District staff, including Christopher McVoy and Martha Nungesser. Individual chapter authors addressed comments for their chapters and the editors addressed comments in all chapters. We did our best to address most comments, but in some cases our opinions differed or addressing the comment was outside the scope of this document. We apologize for comments that may not have been adequately addressed.

We acknowledge and thank each individual, and those we may have inadvertently missed, for their contributions that were essential for the success of this effort. We also acknowledge the support of the Restoration Coordination and Verification (RECOVER)

teams that encouraged us to implement, automate, and document the habitat suitable indices. Thanks to the Committee on Restoration of the Greater Everglades Ecosystem (CROGEE) and Stephen Parker, Director of the National Resource Council's (NRC) Water Science and Technology Board, for their support, encouragement, and recognition of the value of this effort.

Finally, a big thanks to Kimberly Jacobs, our technical editor, for her high quality work and for squeezing this project in with other priorities.

Kenneth C. Tarboton[1], Michelle M. Irizarry-Ortiz[1], Daniel P. Loucks[2], Steven M. Davis[1] and Jayantha T. Obeysekera[1]

July 2004

1. South Florida Water Management District

2. Cornell University

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LIST OF ACRONYMS AND ABBREVIATIONS

ATLSS	Across Trophic Level System Simulation
BPSI	benthic periphyton suitability index
C&SF	Central and Southern Florida
CDD	cumulative drought duration
CERP	Comprehensive Everglades Restoration Plan
CFD	cumulative flood duration
CROGEE	Committee on the Restoration of the Greater Everglades Ecosystem
DDI	daily drought index
DFI	daily flood index
ELM	Everglades Landscape Model
EPSI	epiphythic periphyton suitability index
FPSI	floating periphyton suitability index
HEP	habitat evaluations procedures
IFIM	instream flow incremental methodology
LNWR	Arthur R. Marshall Loxahatchee National Wildlife Refuge
MAMDI	mean annual minimum drought index
MAMFI	mean annual minimum flood index
NRC	National Research Council
NSM	Natural System Model
PSR	predicted species richness
RECOVER	Restoration Coordination and Verification
Restudy	Central and Southern Florida Project Comprehensive Review Study
SFWMD	South Florida Water Management District
SFWMM	South Florida Water Management Model
SI	suitability index
SI_{depth}	water depth suitability index
SI_{land}	landscape-level habitat suitability index
$SI_{recession}$	water recession suitability index
SI_{WB}	wading bird suitability index
SI_{wish}	wading bird suitability index for white ibises and small herons

SI_{wost}	wading bird suitability index for wood storks
SRSI	species richness suitability index
TISI	tree island suitability index
USACE	United States Army Corps of Engineers
USFWS	United States Fish and Wildlife Service
WCA	Water Conservation Area

CHAPTER 1

Introduction

Daniel P. Loucks[1] and Kenneth C. Tarboton[2]

Overview

The Greater Everglades ecological system, extending south of Lake Okeechobee in South Florida (**Figure 1-1**), provides habitat for a unique and diverse variety of animal and plant life. It also contributes to South Florida's water supply, flood control, and recreation. Historically, the Everglades was a free-flowing “river of grass” that provided clean water from Lake Okeechobee to Florida Bay (Douglas 1947). Overflow from the lake flowed south as sheet flow, over very wide and flat landscapes characterized in part by the microtopographic and vegetation features (**Figure 1-2**) that supported this unique ecological system.

Anthropogenic activities (including drainage, urbanization, and agriculture) have reduced the size and biodiversity of the Everglades ecosystem. They have also altered its hydrology. The result has been a reduced and degraded habitat for a wide variety of plant and animal life. Some species of plant and animal life are in danger of becoming extinct.

In an attempt to reverse the loss of this unique ecosystem, the Florida Legislature enacted the Everglades Forever Act (Section 373.4922, Florida Statutes). This act allocates funds to restore the Everglades “…both in terms of water quality and water quantity … in a manner that is long term and comprehensive.” More recently, Congress approved the Comprehensive Everglades Restoration Plan (CERP) in the Water Resources and Development Act of 2000 (WRDA 2000) for restoring and protecting the South Florida ecosystem. This plan focuses on “getting the water right.” Getting the water right involves four fundamental attributes: its quantity, its quality, its timing, and its spatial distribution.

Getting the water right is really a surrogate for getting the water-dependent ecology right. This report describes an approach to estimating the impact of alternative water management policies on the ecosystem without specifically modeling the behavior of various species within the ecosystem. It is an intermediate approach, assessing system performance with a greater focus on the ecology than solely hydrology but at the same time recognizing it is less than a full-scale multispecies ecological simulation. It attempts to relate various hydrologic variables to the relative condition of the habitat for selected species and features of the ecosystem.

1. Cornell University

2. South Florida Water Management District

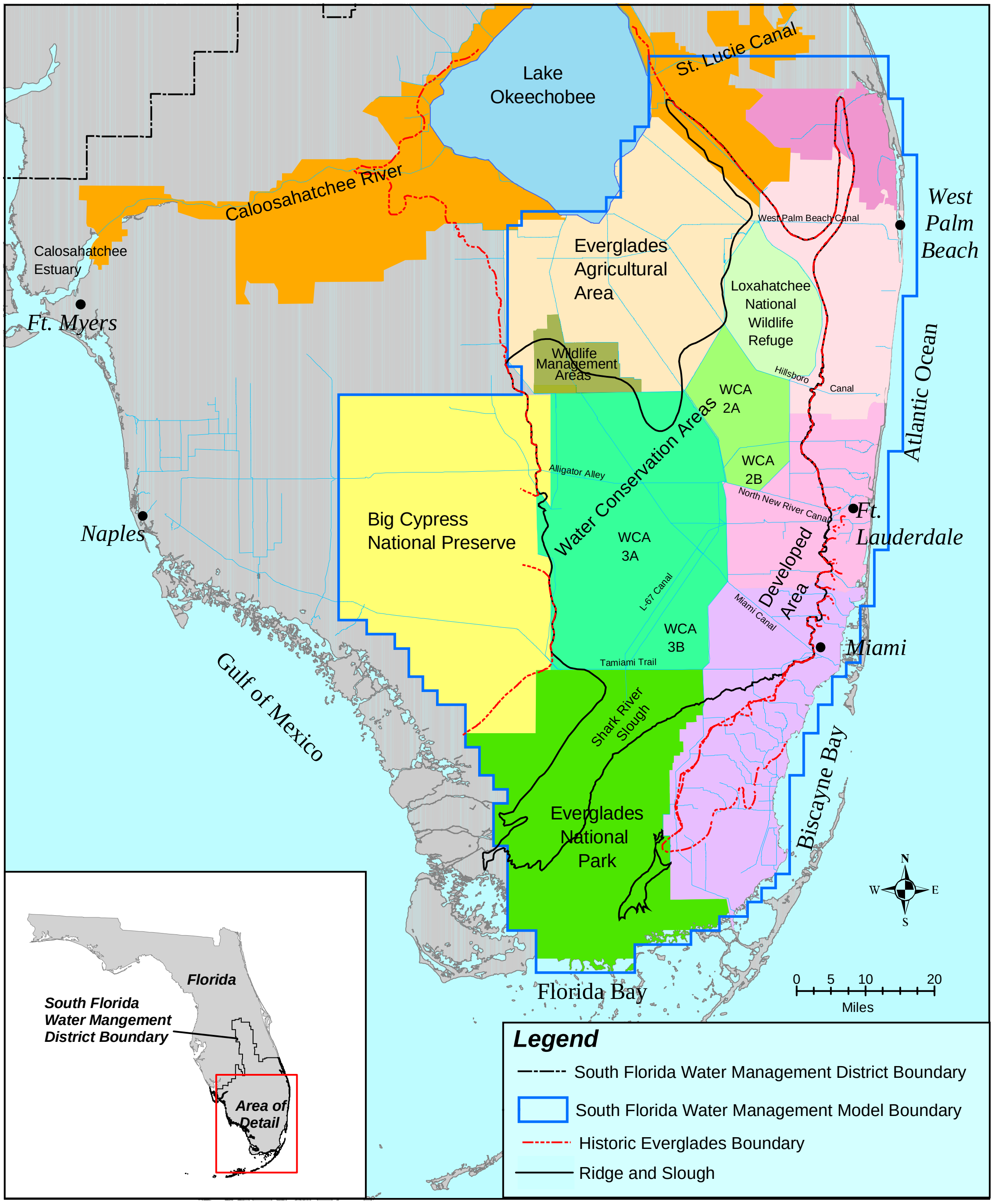

Figure 1-1. Greater Everglades region within which selected habitat suitability indices for evaluating water management alternatives are produced. Key features and geographical areas referred to later in this document are indicated in the figure.

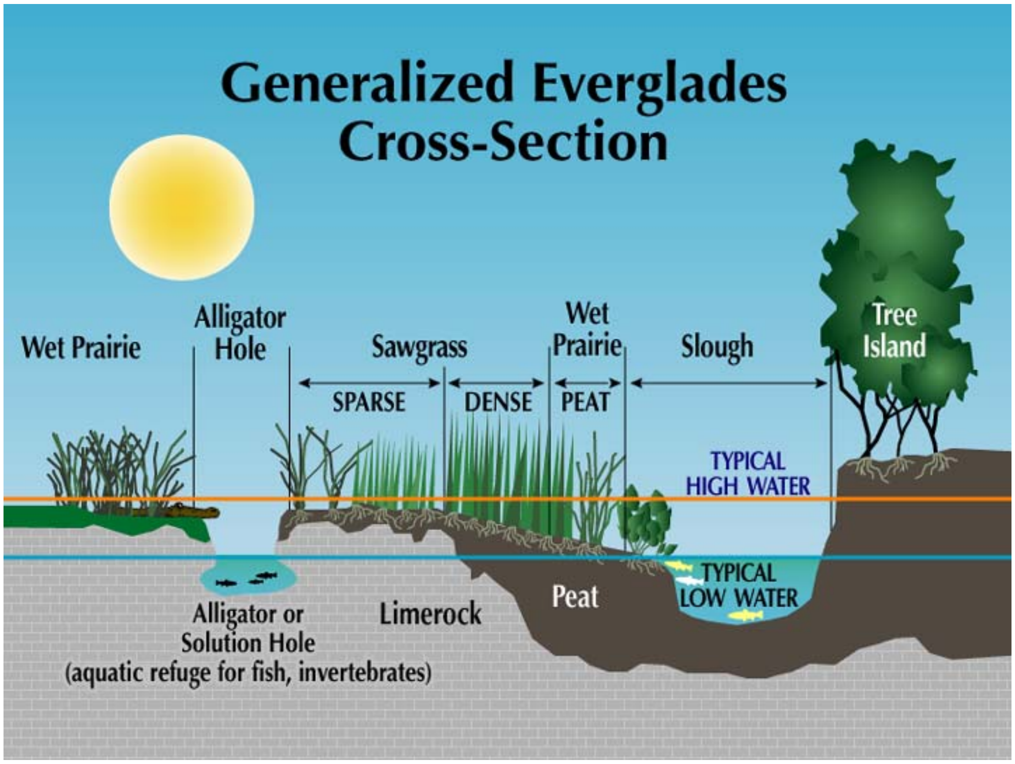

Figure 1-2. A characterization of a major portion of the Everglades in South Florida.

The remainder of this chapter provides more detail on the CERP and on how to move from "getting the water right" to "getting the habitat right" using water-dependent habitat suitability indices.

Comprehensive Everglades Restoration Plan

The Water Resource Development Acts of 1992 and 1996 (WRDA 1992, 1996) authorized the United States Army Corps of Engineers (USACE) to develop a comprehensive plan to restore and preserve the Everglades' ecosystem, while also enhancing water supply and maintaining flood protection. The development of this plan was co-sponsored by the USACE and the South Florida Water Management District (SFWMD). A system-wide approach to managing the region's water resources was adopted during the development of a comprehensive Everglades restoration plan by a team of ecologists, hydrologists, engineers, and other professionals from more than 30 federal, state, tribal, and local agencies. This effort was commonly called the Restudy. This comprehensive plan was published in the *Central and Southern Florida Project Comprehensive Review Study Final Integrated Feasibility Report and Programmatic Environmental Impact Statement* (USACE and SFWMD 1999). The Comprehensive Everglades Restoration Plan (CERP) was approved by Congress on December 11, 2000 (WRDA 2000).

The CERP provides the road map for restoring and protecting the South Florida ecosystem. This plan focuses on “getting the water right” by addressing four fundamental issues: the quantity, quality, timing, and distribution of water. Approximately 8 billion dollars, evenly divided between the state and federal governments, are planned to be spent on this restoration effort over the next several decades.

In summary, the CERP is to provide an integrated adaptive approach for restoring the ecosystem, for increasing the amount and reliability of water supplies, and for providing protection from flood damages (USACE and SFWMD 1999). The plan is seen as a vital step toward establishing a sustainable economy and ecosystem in South Florida. Three additional feasibility studies, Florida Bay and the Florida Keys, Southwest Florida, and a Comprehensive Integrated Water Quality Plan, will add information and details to enhance the restoration of the South Florida ecosystem.

Getting the Water Right

The current Everglades are only about half the size they were a century ago. While restoring their historic size is not feasible, the remaining Everglades ecosystem is to be restored by managing water in ways to reestablish historic (and hence assumed to be the most preferred) conditions. Proper water management is considered the key to ecosystem restoration in South Florida. Scientists, engineers, and other specialists working on the Restudy determined that the problems in the Everglades and the entire South Florida ecosystem were primarily the result of past water management practices and related development activities. Both the problems of declining ecosystem health and the solutions to Everglades' restoration have been framed by four interrelated factors: the quantity, quality, timing, and distribution of water. Water in the *right distribution*, at the *right time*, in the *right quantity* and *quality*, is considered a major determinant of ecosystem dynamics that support life in the Everglades.

Quantity

Significantly less water flows through the Everglades ecosystem today compared to a century ago. An average of about 1.7 billion gallons of water that once flowed through the ecosystem each year is currently discharged to the ocean or gulf. A key goal of the CERP is to capture most of this water in surface impoundments and underground aquifers, where it will be stored until it is needed. These storage facilities are needed to ensure a reliable, adequate supply of fresh water for the environment, as well as for urban and agricultural users. Of the “new” water captured by implementing the CERP, approximately 80 percent will to go to the environment and 20 percent will be used to enhance urban and agricultural water supplies.

Quality

The quality of water in the South Florida ecosystem has decreased significantly as agricultural and urban development has occurred. Excess phosphorus, mercury, and other constituents are now found in the region’s water. Similar signs of contamination are

evident in the waters of the Everglades' water conservation areas, the coastal estuaries, Florida Bay, and the Florida Keys. Implementation of the CERP will improve the quality of water discharged to natural areas by first directing it to surface storage reservoirs and wetlands-based stormwater treatment areas. Further improvements in water quality will be needed to meet quality standards considered necessary for restoration of the original ecosystem character.

Timing

Seasonal fluctuations in water depths were vital to the historical functioning of the Everglades ecosystem. Human activities have tended to decrease average water depths, while at the same time increase the typical range or amplitude of seasonal depth fluctuations. Restoring natural variations in water flows and levels is an integral part of the CERP. An operational plan that mimics natural rainfall patterns will enhance the timing of water sent to the water conservation areas, Everglades National Park, and other wildlife management areas.

Distribution

The areal extent and movement of water through the system is the final factor in the water equation. Over 50 percent of the original Everglades have been lost to urban and agricultural development. That which remains has been separated, or compartmentalized, by canals and levees. To improve the connectivity of, and enhance sheet flow through, natural areas, more than 240 miles of levees and canals are to be removed within the Everglades. Some 20 miles of the Tamiami Trail (U.S. Route 41) are to be rebuilt with bridges and culverts, allowing water to flow more naturally south into Everglades National Park. In the Big Cypress National Preserve, the levee that separates the preserve from the Everglades is to be removed to restore more natural overland water flow.

Plan Cost - Hydrology - Ecology Trade-off

Implementing all these engineering projects to get the water right will be expensive. The estimated 7.8 billion dollars (in 1999 dollars) needed to implement the CERP will be spent over many years and will be shared by the federal government and the State of Florida. Once, and if fully, implemented, over 180 million in current dollars will be needed each year to operate, maintain, and monitor the CERP, especially if predrainage hydroperiods and water quality concentrations are to be achieved.

Can anyone be sure that the political will to continue with this effort will be sustained at this level of expenditure on into the coming decades, let alone the coming century? What if for any economic or other reason (e.g., defense spending or nation building) the hydrologic targets with respect to quantity, quality, timing, and location cannot quite be met? Or being optimistic, what if there is more money to spend? What ecological impacts might result from various deviations from preselected hydrologic targets? To address these questions, one needs to link the four components of hydrology

directly to ecology, for it is ecology, not hydrology, that is of primary concern. One step towards directly achieving the ecological restoration objective is to get the ecological habitat right, at least for a variety of important indicator species and features of the ecosystem.

From "Getting the Water Right" to "Getting the Habitat Right"

Getting the ecological habitat right is only a first step on the way to being able to model and predict ecological responses to water management policies. Several ecological models for the Everglades have been under development for some years. This very challenging work continues. The step of linking habitat suitability indices to hydrology, described herein, is in no way a substitute for the more fundamental effort to continue developing ecological models for the Everglades. In fact, the identification of habitat suitability indices has been facilitated by these efforts to develop more comprehensive ecosystem models. Sklar et al. (2001) provides an excellent review of these models.

Getting the water right is part of a larger effort to restore the ecosystem to a sustainable healthy state. Considerable effort has been spent on developing conceptual ecological models defining the chain of cause-and-effect events or linkages between water and land management actions and the impact on specific ecosystem species in specific regions within the Everglades (Ogden and Davis 1999, RECOVER 2003). These conceptual ecological models (for example **Figure 1-3**) are not quantitative, but nevertheless, help identify the links between hydrologic characteristics and the relative condition of particular indicator species or features of the ecosystem. In this study, conceptual ecological models were used to help define water-dependent habitat suitability indices for selected ecosystem indicator species and landscape features. These suitability

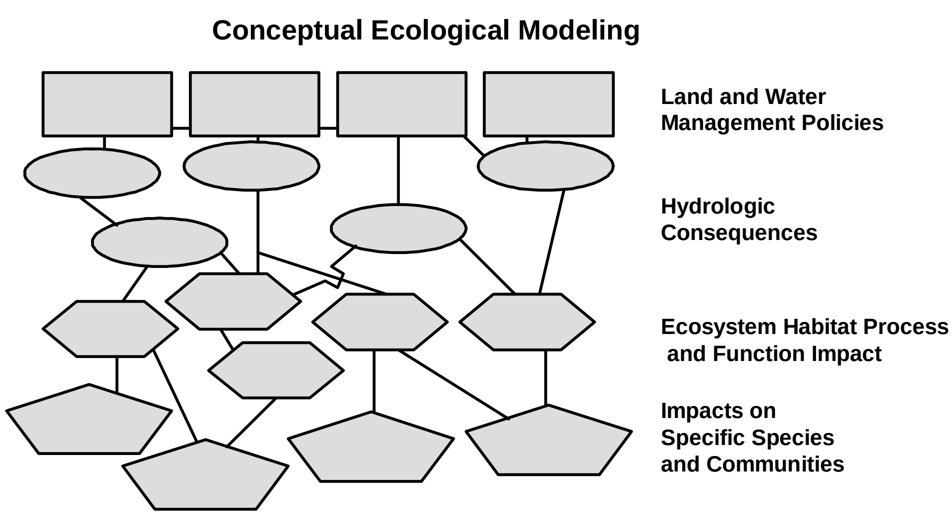

Figure 1-3. Schematic of a typical conceptual ecological model used to identify the important links between land and water management actions and ecosystem species response.

indices together with the hydrologic simulation models used in the development of the CERP provide estimates of the relative impact of alternative hydrologic regimes on various species' habitats and landscape features.

Habitat Suitability Indices

Habitat suitability indices have been used during the past two decades to define, in relative terms, the quality of the habitat for various wildlife species, especially fish. The United States Fish and Wildlife Service (USFWS) developed a series of habitat suitability index models to be used with habitat-based evaluation techniques, such as the Habitat Evaluation Procedures (HEP) (USFWS 1980) and the Instream Flow Incremental Methodology (IFIM). These techniques are designed for inventory, impact assessment, and the development of fish and wildlife management plans (see, for example, http://www.nwrc.gov/wdb/pub/hsi/hsiintro.htm).

Habitat suitability indices (USFWS 1981) can be used as a first approximation toward quantifying the relationships identified in the various conceptual ecological models (**Figure 1-3**). To illustrate the application of habitat suitability indices to the Everglades, we selected a number of important indicator species and landscape features for specific regions of the Everglades. The next step was to identify hydrologic variables that affect those species or landscape features. For this study, these key hydrologic variables were identified in a series of workshops attended by experts in the study of each particular species or landscape feature. The identified hydrologic variables are functions of the water quantity, quality, timing, and distribution; each of which can be modeled and managed in South Florida. Next, habitat suitability functions of these hydrologic variables were defined. These functions, ranging from 0 (least desirable) to 1 (optimum), indicate the relative condition of the indicator species or landscape features depending on the value of the hydrologic variables.

Once defined, these functions can be used to estimate the relative suitability of the resulting habitat for each indicator species or landscape feature over the relevant domain for application of the particular index or specific regions of interest associated with any specific simulated water management policy. The habitat suitability functions may change as new knowledge is obtained.

The purpose of this report is to describe the methods used to define these functions and show how they can be used to compare alternative water management plans or policies. The particular functions defined in this report merely illustrate the approach being used to evaluate alternative water management plans. *They do not necessarily define the specific habitat suitability functions that will be used in evaluating Everglades restoration plans. The specific habitat suitability indices to be used for evaluating alternatives during the implementation of the CERP will be defined after further study and review.*

Document Organization

The remainder of this document describes the steps taken to define the hydrologic variables and corresponding habitat suitability functions associated with several selected indicator species and landscape features in selected regions of the Everglades. The methodology used to identify key indicator species and the hydrologic simulation models that provide input to the habitat suitability index models are described in Chapter 2. The hydrologic (quantity) simulation models used in this study include the South Florida Water Management Model version 3.5 (SFWMM) and the Natural System Model version 4.5 (NSM).

Chapters 3 through 8 describe in more detail each specific habitat suitability index and its hydrologic variables. Initial results showing the relative performance of each index under simulated natural, current, and restored system hydrologic conditions are presented. These chapters are ordered starting from landscape (space-dependent) habitat suitability indices up the trophic chain to biotic (space/time-dependent) indices. Ridge and slough (Chapter 3), tree islands (Chapter 4), and periphyton (Chapter 5) are time-averaged, but spatially-variable habitat suitability indices. Fish (Chapter 6) and alligators (Chapter 7) are spatially- and temporally-variable indices. The suitability for wading birds (Chapter 8) varies in time and is not dependent on location as long as sufficient suitable habitat occurs somewhere within a relatively large area.

Comparisons between ecological indicators are presented in Chapter 9 to show how suitability indices can be used to highlight trade-offs between ecological indicators in comparing alternative water management strategies. Chapter 10 provides a synthesis of the linkages between the different habitat suitability indices within the context of the overall system. Finally, Chapter 11 presents some conclusions.

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WRDA. 1996. Water Resources Development Act of 1996. Public Law No. 104-303, signed October 12, 1996. Section 528 of the act describes authorizations specific to Everglades and South Florida Ecosystem Restoration.

WRDA. 2000. Water Resources Development Act of 2000. Public Law No. 106-541, signed December 11, 2000. Title VI, Section 601, of the act, describes authorizations specific to the Comprehensive Everglades Restoration Plan.

CHAPTER 2

Methodology and Modeling Approach

Daniel P. Loucks[1], Jayantha T. Obeysekera[2], and Kenneth C. Tarboton[2]

Overall Methodology

Steps to define habitat suitability functions involved first identifying key indicator species or landscape features, then determining which hydrologic variables best quantified impacts to the selected species. Then, relationships between the hydrologic variables and the species were quantified, verifying these relationships where possible. System-wide simulation models were used to generate hydrologic information used as input to the habitat suitability relationships. Output from the relationships was expressed as time-series or long-term average values, depending on the indicator, and were obtained for multiple locations (model grid cells) or averaged over the domain of the model. In some cases, relationships were combined to provide a composite, or overall, indicator value or a series of values. The following sections describe the steps in obtaining habitat suitability indices in more detail and provide some information about the models chosen to generate hydrologic data for this study.

Identifying Indicators

The first step in this process of defining habitat suitability functions was to identify the principal indicator species or landscape features that would serve as a surrogate for the entire ecosystem in specific regions of the Everglades. In this study we chose six different indicators of ecosystem condition. Three indicators were landscape-scale features that vary over space but not significantly over the simulated thirty-year time. The landscape-scale indicators, namely ridge and slough landscape, tree islands, and periphyton, were considered functions of hydrologic conditions over long periods of time, on the order of decades. Two of the selected indicators, fish and alligators, varied over time and space. One indicator, wading birds, varied only over time. The wading birds habitat suitability index is not dependent on location as long as sufficient suitable habitat is available within the overall region. The selected indicators are illustrated in **Figure 2-1**.

1. Cornell University
2. South Florida Water Management District

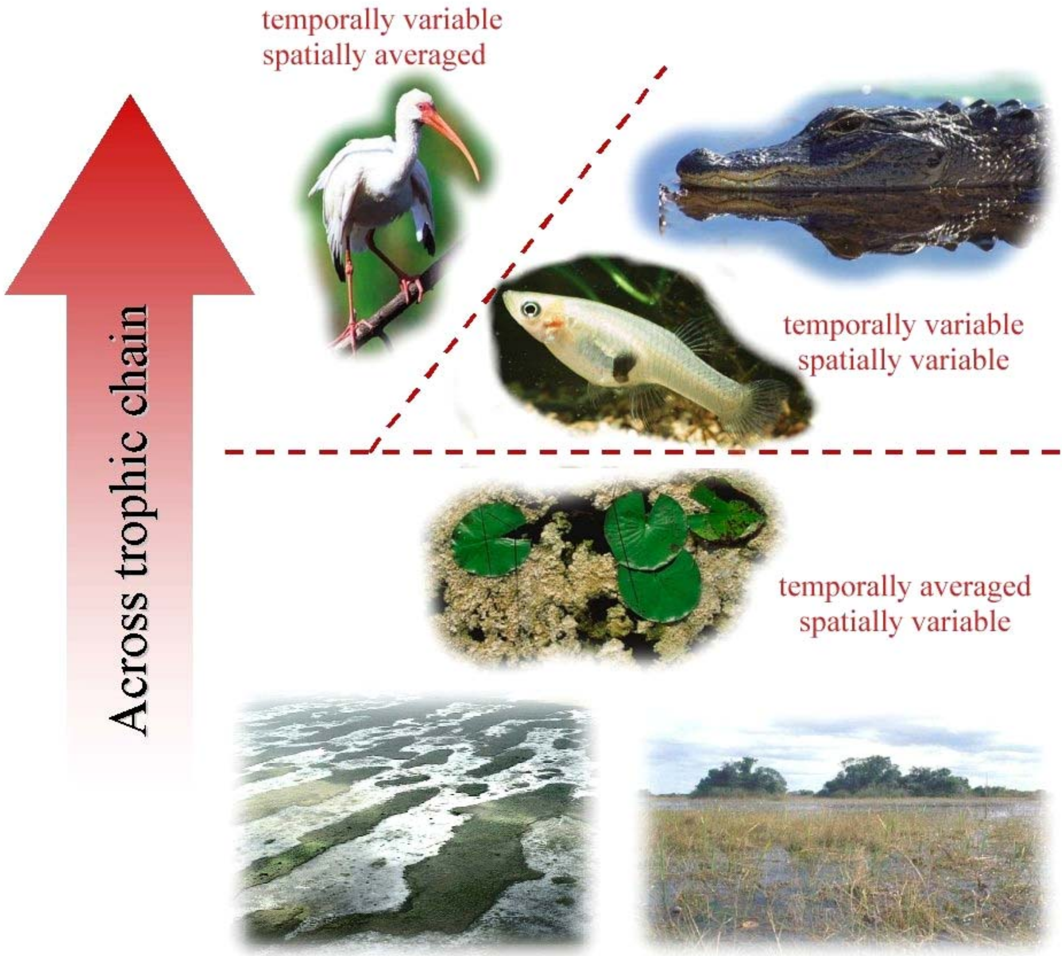

Figure 2-1. Indicator features of the Everglades selected for this study and their relative position across the trophic chain.

Identifying Applicable Area

The pre-drainage Everglades was not uniform throughout; different areas had different ecological and hydrologic characteristics. An important second step therefore was identifying the predrainage extent or "footprint" of each indicator species or feature. This was necessary to ensure that the indices would follow a central tenet of Everglades restoration: areas are to be restored as close to their original condition as possible.

Determining Hydrologic Variables

Following identification of the indicator feature or species and its applicable area the next step was to determine which hydrologic variables, attributes, or characteristics affect the selected indicator features or species. These hydrologic variables were functions of what is managed (i.e., water depths, flows, and hydroperiods) and the rates of change in these variables. Variables may apply only in particular time periods and particular

locations, in the same way as individual ecosystem indicators have an applicable area. Correct determination and quantification of the specific hydrologic variable or stressor that affects the ecosystem indicator is critical in quantifying the habitat suitability index. Hydrologic variables ranged from simple, such as long-term hydroperiod (time of ponding), which was used for periphyton, to complex, such as the rate of change of water depth within a certain time window relative to the depth of water, which was used for wading birds. Examples of hydrologic variables include the following:

- Water Depth
  - average (weekly, monthly, annual, between specified dates)
  - minimum, maximum, above/below thresholds
  - relative to depths at earlier dates
  - rates of recession
- Flow Direction
- Flow Velocity
- Hydroperiod
  - duration between specific dates (discontinuous, continuous)
  - time since last dry period
  - period below/above specified thresholds

Each of the above examples can be measured in the field, albeit some with difficulty at regional scales. They also can be simulated using hydrologic models. Their values are influenced by water management policies. The actual variables used for specific habitat suitability indices may be functions or combinations of those examples just listed. For example, wading bird habitat suitability indices may depend not only on the water depth and its drawdown rate in a specific period but also on the habitat suitability index value of a species of fish. The fish habitat suitability value may in turn depend on the hydroperiod durations of several previous years. The next section illustrates the methodology used to define habitat suitability functions for the particular species we selected.

Defining Habitat Suitability Functions

Once the specific hydrologic variables were selected for each species or feature of interest, the next step required identifying the relationship between those variable values (or the values of functions of multiple hydrologic variables) and the relative conditions of the indicator species or topographic features. Such a function is shown in **Figure 2-2**. These functions were based on observed data and the knowledge of those who were involved in this study. Once defined, these habitat suitability index functions were combined in various ways to obtain an overall ecosystem suitability value associated with

any particular water management scenerio. **Figures 2-2** and **2-3** illustrate this procedure. Once such habitat suitability functions were defined, they were used together with time series of hydrologic values to create a time series of habitat suitability values, as shown in **Figure 2-3**.

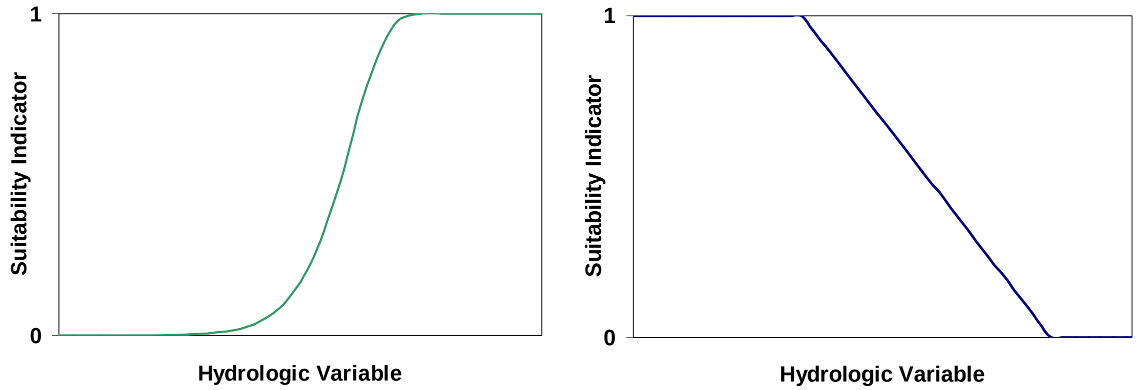

Figure 2-2. Two performance suitability indicators expressed as functions of hydrologic variables.

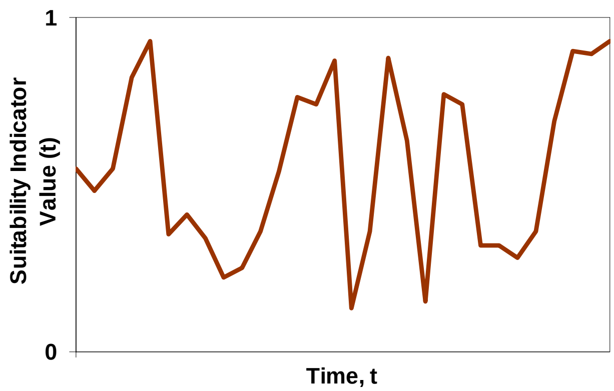

Figure 2-3. A time series of values of a suitability indicator derived from a time series of hydrologic variable values mapped into a habitat suitability indicator function such as shown in **Figure 2-2**.

Thus, the time series of suitability indicator values, shown in **Figure 2-3**, is a function of the time series of hydrologic variable values generated from a model simulation of a particular management plan or policy. These time series were characterized using various statistical measures including the following:

- Mean value
- Variance
- Reliability based on a specified threshold value
- Resilience based on a specified threshold value
- Vulnerability in duration or extent, again based on specified threshold value

Composite value based on time series values of multiple suitability functions were obtained various ways whether over time, as shown in **Figure 2-4**, or over space. The best way differed for the different indicators. Geometric means, weighted arithmetic means, and maximum or minimum values were used to obtain composite performance indicator values. The methods selected for combining different habitat suitability functions for the same ecosystem feature or species were determined during the calibration procedure.

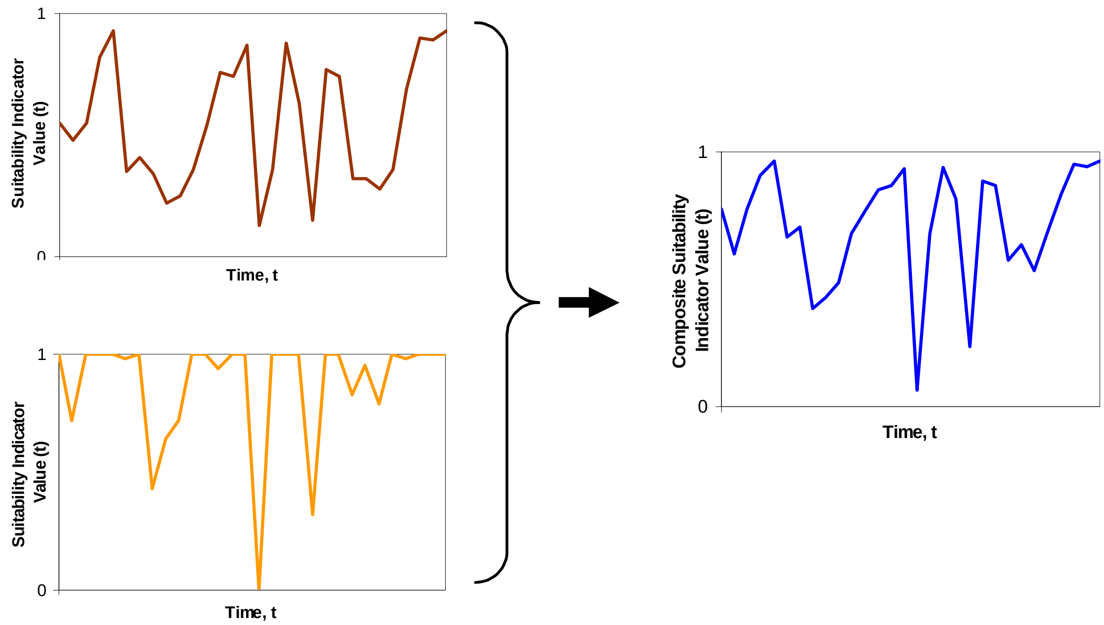

Figure 2-4. Creating a composite suitability indicator time series from multiple suitability indicator time series.

In addition to the specific statistical measures mentioned above, individual or composite suitability indicator time series values were summarized graphically or pictorially in a variety of ways. One way that defined and plotted probability of exceedance functions is shown in **Figures 2-5** and **2-6**. The areas under such functions are the mean suitability values.

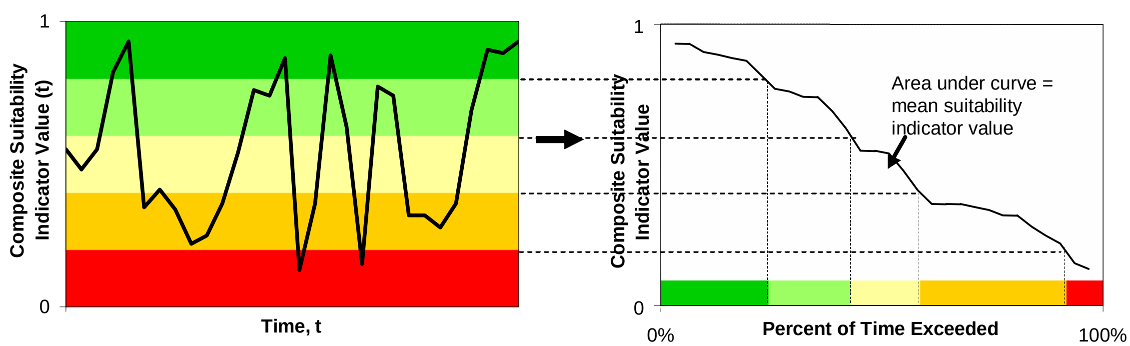

Figure 2-5. Establishing color-coded zones of indicator values for subsequent statistical analyses.

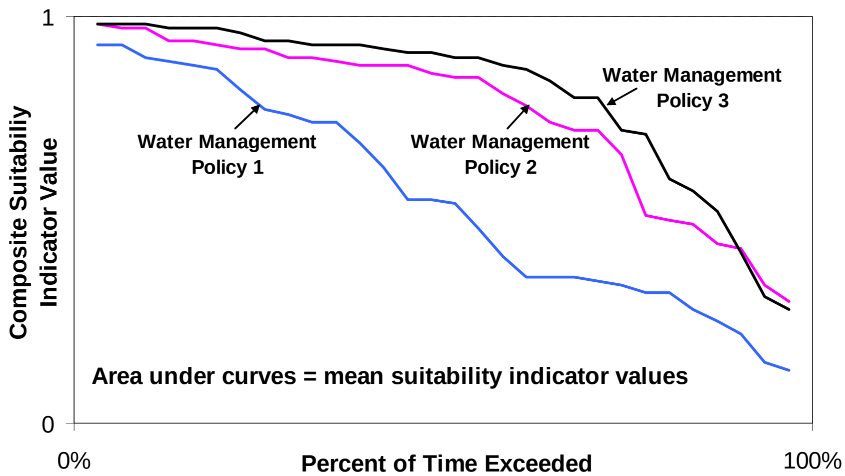

Figure 2-6. Exceedance functions for a particular composite suitability indicator under three different water management policies. The difference between the mean values is a measure of relative impact of different management alternatives.

In addition, color-coded maps were used to show ranges of suitability values over space at specified times. These are particularly useful in highlighting the challenge of creating a habitat that is perfect for all species at all times over the entire Everglades region. Ecology, at least in the Everglades, is in part about who is eating whom, and the condition of those being eaten is affected by the condition of those who are doing the eating!

For this study, we identified the hydrologic variables affecting the six selected ecosystem features and species: ridge and slough topography, tree islands, periphyton (algae), fish, alligators, and wading birds (**Figure 2-1**). Also estimated were the functions relating those hydrologic variables to the relative condition of the indicator. Multiple functions for the same indicator were then combined in ways that best corresponded to the observed data or expert judgment during the calibration procedure. It is important to notice that the functions developed for different ecosystems have different levels of complexity and have been subject to different degrees of calibration and verification. Although many of these functions will continue to improve over time, this exercise demonstrates one relatively simple way to obtain preliminary answers to questions involving trade-offs between water management or restoration plans and costs and ecological habitat impacts.

The next six chapters describe in more detail this process for the six specific indicators. These chapters are ordered starting from landscape (space-dependent) habitat suitability indices to biotic (space- and time-dependent) habitat suitability indices and moving across the trophic chain (**Figure 2-1**). Suitabilities for ridge and slough, tree islands, and periphyton are time-averaged but spatially-variable. Suitability for fish and alligators are spatially- and temporally-variable. Suitability of wading birds varies in time and is not dependent on location as long as sufficient suitable habitat is available within a larger area.

Hydrologic data or output from any model can be used as input to the habitat suitability indices. The most widely used regional hydrologic models in South Florida are the South Florida Water Management Model version 3.5 (SFWMM) and the Natural System Model version 4.5 (NSM). These models were used to simulate the alternatives on which the Comprehensive Everglades Restoration Plan (CERP) was based, and are also used in weekly and monthly operational planning for the operation of the Central and Southern Florida (C&SF) Project. Output from these models has been automated and processed into hundreds of different performance measures, and future automation of habitat suitability indices using output from the SFWMM and NSM is feasible. Hence, the SFWMM and NSM were selected as the models for producing hydrologic output on which to base the habitat suitability indices in this study.

The habitat suitability indices described here could be applied to other regional hydrologic models as well. Results from applying the habitat suitability indices to model output from the natural (NSM), current (1995 Base, SFWMM), and restored system (D13RNov98, SFWMM) simulations are presented on the next six chapters. A performance measure set comparing these runs can be found on the Restudy Modeling web page at http://www.sfwmd.gov/org/pld/restudy/hpm/ (see September 21, 2001 posting under "What's New" section). More details on the SFWMM and the NSM are given in the next section.

South Florida Water Management Model

The SFWMM is an integrated surface water-ground water model that simulates the hydrology and management of the South Florida water resource system from Lake Okeechobee to Florida Bay (**Figure 1-1**). Major components of the hydrologic cycle, including rainfall, evapotranspiration, overland flow, ground water flow, canal flow, and seepage beneath levees, are simulated. Additionally, the model simulates the operations of the C&SF Project components including major wellfields in the developed lower east coast, impoundments, canals, pump stations, and other water control structures. The ability to simulate various hydrologic scenarios under natural conditions using the NSM (**Figure 2-7a**) and under current conditions using the SFWMM (**Figure 2-7b**) facilitates the investigation of trade-offs between different water supply, flood control, and environmental demands in various subregions. The models have been calibrated and verified using water level and discharge measurements at hundreds of locations distributed throughout the region within the model boundaries. Documentation (SFWMD 1999), including model calibration, verification, and peer review, can be viewed at http://www.sfwmd.gov/org/pld/hsm/models/sfwmm.

The model uses a daily time step, consistent with the minimum time increment for which input climatic data are available and can be simulated for time periods ranging from one month to 36 years. A distributed, finite-difference modeling technique is used to model the gridded portion of the model domain with 2-mile by 2-mile square grid cells. Lumped parameter modeling approaches are used for Lake Okeechobee and the northern lake service areas, which include the Caloosahatchee and St. Lucie basins. Homogeneity of physical and hydrologic characteristics are assumed within each grid cell. The grid

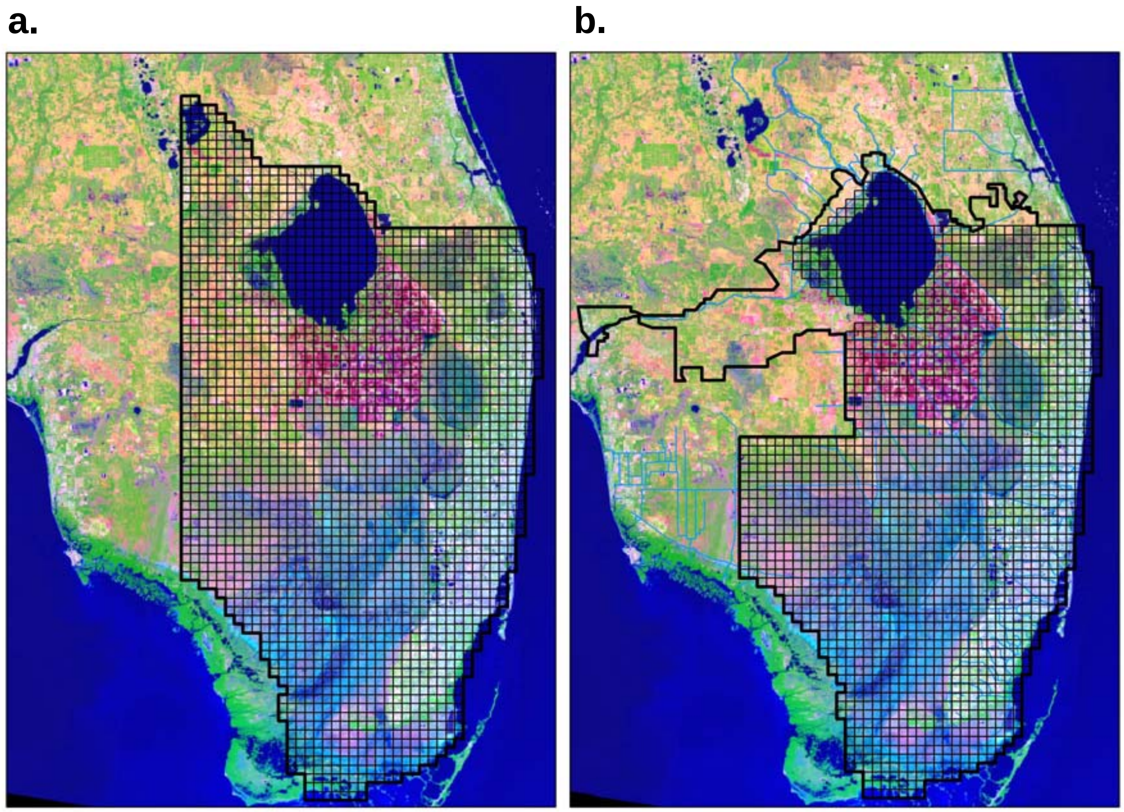

Figure 2-7. Domain and grid for a) NSM and b) SFWMM.

discretization in the SFWMM is sufficiently fine to describe the solution to the overland and ground water flow equations with reasonable resolution and to minimize numerical errors (Lal 1998).

In the version of the SFWMM (version 3.5) used in this study, primary dynamic inputs are daily rainfall and evapotranspiration available for the period from 1965 to 1995, which includes both drought and wet periods. Rainfall is estimated from more than 600 stations within the model domain and reference crop evapotranspiration is calculated using the Penman-Monteith method (Monteith 1965) with climatic data from 12 stations. Static inputs include physical parameters such as land elevation, land use, soil properties, aquifer properties, basin definitions, irrigation information and utility demands. The preponderance of the SFWMM code is dedicated to mimicking the complex operational rules that regulate flow into and out of canals and water storage areas. Current or proposed policies and rules for flood control, water supply, and environmental restoration or enhancement are specified in the input. Typically, alternative plans are compared against baseline conditions specified in the model input.

Output from the SFWMM is available in text and binary formats and include several summaries and water budgets. Postprocessing utilities are used to produce extensive sets of performance measure graphics and tables comparing selected SFWMM simulations for alternative water management strategy comparisons.

Natural System Model

The NSM was derived from the SFWMM using the same algorithms as the SFWMM and, where possible, calibrated SFWMM model parameters. The NSM (SFWMD 1998) differs from the SFWMM in that it does not simulate the influences of any man-made features and uses estimates of presubsidence topography and predevelopment vegetation cover. The NSM simulates a predrained hydrologic response of the system to the same climatic inputs as the SFWMM, allowing for meaningful comparisons between the modeled response of the managed system and the natural (predrained) system.

It is difficult to determine how closely the NSM resembles the actual predrainage system because predrainage measurements corresponding to NSM simulated output are either nonexistent or not directly comparable. Two sources of uncertainty are associated with model input; estimated predrainage topography and hydraulic resistance. The NSM uses calibrated current system hydraulic resistance values from the SFWMM. The absence of present day analogs for predrainage vegetation and the presence in the current system of large areas with little or no flow contribute to the uncertainty of these values. Comparison of NSM output with an extensive historical study of predrainage hydrology (McVoy et al. in review), indicates that simulated water depths appear generally to be shallower than those compiled in the historical study; simulated annual variation (rise and fall) of water depths appears to be smaller than historical; and simulated spatial pattern of water depths is different. The shallower depths and smaller range may be related to a combination of the 1965-1995 period of weather data being drier than the long-term average and possibly to under simulation of inputs from Big Cypress and Lake Okeechobee. The differing spatial patterns may be related to the assumed predrainage topography.

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CHAPTER 3

Ridge and Slough Landscape Index

Christopher W. McVoy[1] and Kenneth C. Tarboton[1]

General Description

While most habitat suitability indices in this report will focus on species or groups of species, this chapter focuses on suitability for a physical region of the Everglades, the ridge and slough landscape. An analogy can be drawn to a house and its inhabitants. If the inhabitants are in any way tied to a specific house, then the soundness of that house in some, perhaps great, measure determines the health of its inhabitants. Much of the presently remaining Everglades, consisting of Everglades National Park, and Water Conservation Areas 1, 2, and 3 **Figure 1-1**, was once part of the predrainage ridge and slough landscape or the extensive “house” as shown in **Figure 3-1**. The ridge and slough landscape is delicate, as the critical distinguishing characteristic of this patterned peatland (Wright 1912), its microtopography (**Figure 3-2**), was formed simply by peat soil, a biologically-active, highly impermanent material. One of the key measures of the “health” of the ridge and slough landscape, the microtopographical elevation difference that distinguished sawgrass ridges from open water sloughs, has in fact been decreasing under postdrainage conditions. Field observations indicate that loss of the characteristic microtopography can ultimately transform this landscape into uniform sawgrass, a situation much less suitable for native Everglades fauna.

The predrainage ridge and slough landscape included three main components: sloughs, ridges, and tree islands, in order of increasing elevation. The focus of this suitability index is specifically on ridges and sloughs, which originally covered approximately 95 percent of the landscape. The tree islands covering the other 5 percent of the area are sufficiently different and important that they are addressed in a separate index (see **Chapter 4**).

Water has played a central role in creating and maintaining the strongly directional, patterned ridge and slough landscape that is shown in **Figures 3-1**, **3-2** and **3-3** that prevails over much of the Everglades region. The central hypothesis underlying this suitability index is that the original bi-modal configuration of ridges and sloughs that prevailed over much of the Everglades region was, and still is, highly tuned to specific aspects of water depths as well as specific aspects of unimpeded water flow. A corollary hypothesis is that if those specific water depth and flow conditions are not present, restoration will not be achieved, and persistence of the landscape is endangered. The exact

1. South Florida Water Management District

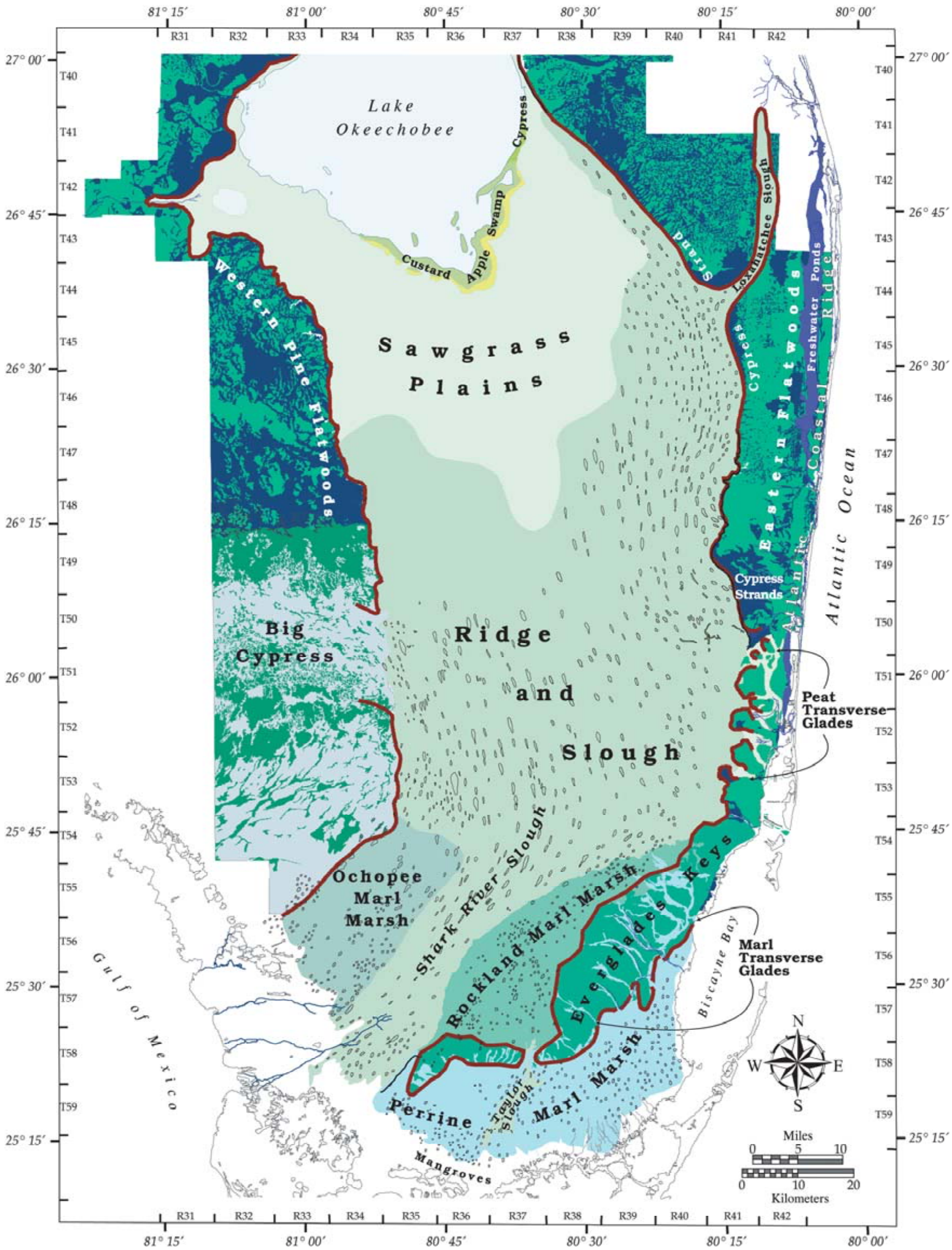


Figure 3-1. Landscapes of the predrainage Everglades and bordering areas, circa 1850 (McVoy et al. in review).

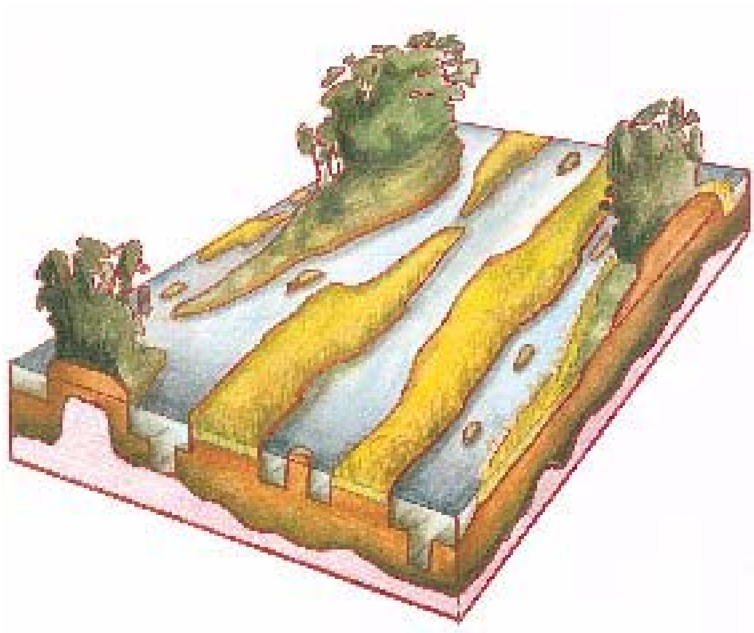


Figure 3-2. Artistic rendition of the predrainage ridge and slough landscape (1-mile by 1.5-mile block). Note relation of landscape pattern (plan view) to underlying peat microtopography (vertical profile).

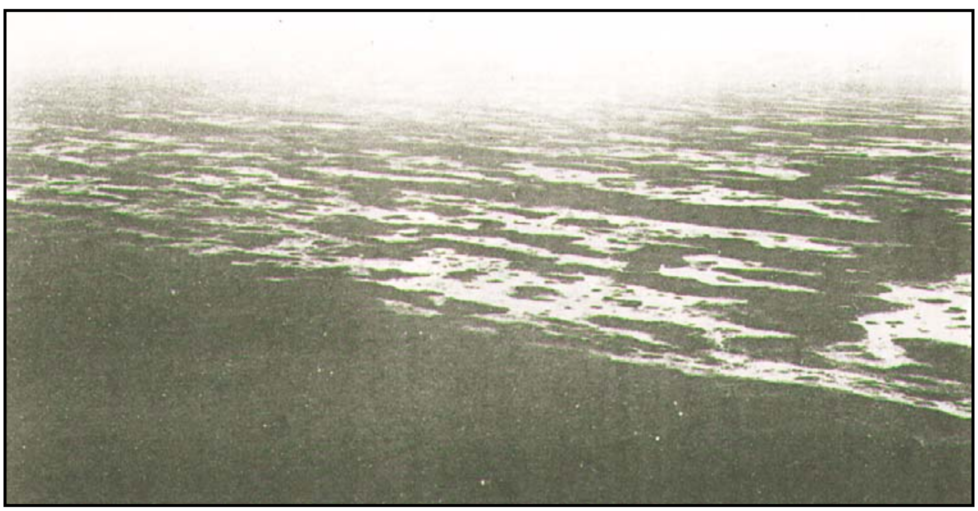


Figure 3-3. Ridge and slough landscape feature in predrainage condition. Aerial view taken in the 1930s shows linear pattern of elongated sawgrass ridges and intervening sloughs (Matlack 1939).

mechanisms responsible for creation and maintenance of the landscape are not completely understood. However, postdrainage compartmentalization of the ridge and slough landscape has created a set of de facto, albeit imperfect, experimental treatments. Within and between them, differing levels of the hypothesized driving variables of water depth and water flow can be found. Empirical observation of the response variable (landscape pattern) suggests that different types of degradation of the original landscape pattern have occurred as shown in **Figure 3-4**, and that the different changes can be related to levels of the independent driving variables (water depth and flow). These observations of the altered, postdrainage landscape, along with a mental template of the original landscape developed from historical information, together form the basis for the indices described in this chapter.

These indices estimate the ability of diverse simulated hydrologic regimes to sustain the microtopography and landscape pattern originally present in the peat (Histosol)-based ridge and slough landscape. The need for such indices arises from the inherent vulnerability of pattern in patterned peatlands in general, and from the observed, significant loss of pattern within the Everglades in specific.

Hydrologic Variables

Several hydrologic variables are considered influential in maintaining the ridge and slough landscape features. These variables, which include water depth and its annual variation, flow velocity, and flow direction, are based on the assumption that the continuous directional and patterned peatland, called the ridge and slough landscape, originally formed under natural predrainage conditions. Under predrainage conditions, the vegetation pattern was the direct result of water depth differences which in turn are created by microtopographic variations in the peat surface. This microtopography was inherently unstable. Under equilibrium, the peat surface would become flat across the whole landscape. The configuration of deeper sloughs next to shallower ridges implies the presence of some processes that counterbalanced the natural tendency for the sloughs to fill in and the ridges to disintegrate. These processes were both hydrologic and biological.

Optimum conditions for sawgrass as well as predrainage historical evidence suggest that hydroperiods on sawgrass ridges were typically less than 12 months. For one or two months of the year, the water depth would drop somewhat below surface elevations, exposing the peat soil to oxidative decomposition and subsidence, which lowered the elevation of the peat surface. Peat accumulating from annual sawgrass growth would act in the opposite direction, tending to raise the peat surface. Ridges grew only up to some height above the long-term average water depth, with the height determined by the balance of accumulation and decomposition. Net downstream transport of organic material might have played an additional role, but this seems unlikely given the density of sawgrass stems along with substantial stabilization of the peat soil by root networks.

The mechanisms for slough maintenance seem likely to have been quite different. Predrainage observations suggest that the sloughs were sufficiently deep and would not typically have dried out each year. This suggests that the mechanism of aerobic

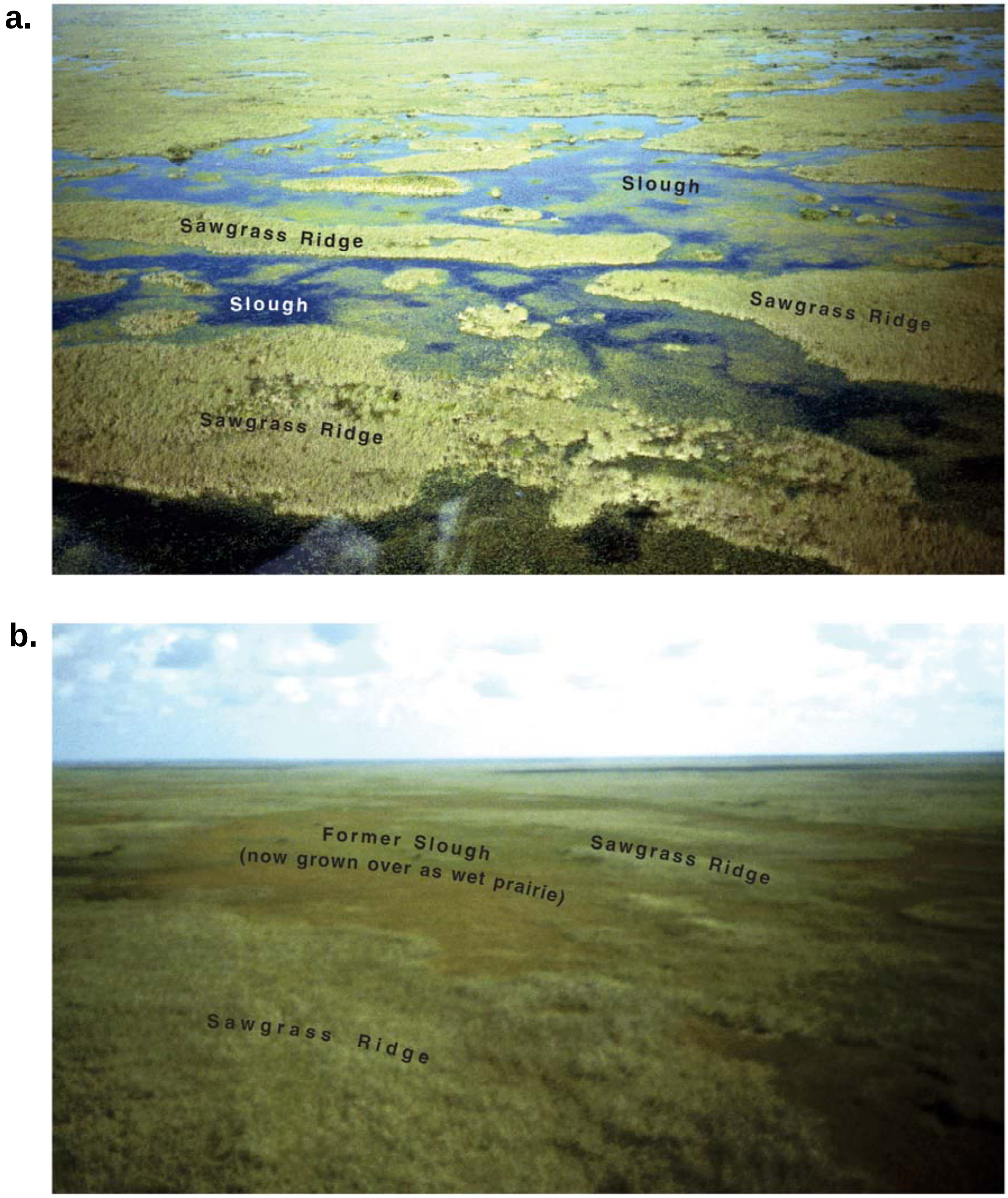


Figure 3-4. Two possible modern (August 1997) analogs for the predrainage ridge and slough landscape. Both photos were taken on the same day, but at different locations, and of areas having different management histories. **a)** Impounded south end of the Arthur R. Marshall Loxahatchee National Wildlife Refuge, showing sawgrass ridges and aquatic sloughs with open water or water lilies. **b)** North end of Water Conservation Area 3A, north of Alligator Alley (I-75), where sawgrass ridges and shapes of sloughs are still recognizable, but the sloughs have completely grown over with emergent vegetation. Traces of the original north northwest-south southeast orientation of sawgrass ridges and sloughs are still visible, but pattern is unclear, and ridges are breaking up into individual patches (McVoy et al. in review).

decomposition did not play a major role, leaving the sloughs more subject to filling in from the accumulation of organic material. Predrainage observations that sloughs were frequently open water with little emergent growth, suggests a mechanism of net downstream transport of organic material to balance in-site production. The predrainage observation of a flocculent layer of loose, organic material found even today in portions of the remnant ridge and slough landscape as well as predrainage observations of water flowing parallel to landscape directionality suggest a possible mechanism for carbon balance in the sloughs (i.e., floc transport counterbalancing floc accumulation). Unrestricted flow paths through the sloughs would be critical to uninterrupted downstream transport of organic material. It is easy to imagine how any significant change in water depths and velocities could have altered this delicate balance resulting in filling-in of the sloughs as has been observed in large areas of former ridge and slough landscape that have converted to dense, uniform stands of sawgrass.

The type of pattern degradation observed today cannot be explained on the basis of altered water depths or hydroperiods alone. A change in a directional flow-related process must also be implicated. The directionality of the ridge and slough region clearly suggests water flow had something to do with the maintenance of the characteristic landscape pattern. Where flows have been blocked or interrupted, directionality has nearly disappeared.

Habitat Suitability Functions for Ridge and Slough

Ridge and Slough Suitability Index

The ridge and slough landscape suitability index consists of four subindices, two each for water depth and for water flow. Together, the four attempt to capture the link between hydrology and landscape pattern. All four subindices are based on the assumption that conditions will be most suitable for maintaining or restoring the landscape when subindex levels are closest to their predrainage levels. The four subindices are 1) average water depth, 2) annual variation (rise and fall) in water depth, 3) flow velocity, and 4) flow direction. The link between landscape and hydrology is assumed to be a temporally-damped one, that is, changes in the landscape pattern are assumed to occur only when long-term average levels of the index actually change. All four subindices are therefore based only on the period-of-simulation average of the South Florida Water Management Model (SFWMM) output (31 years in this case). Output of the ridge and slough indices is therefore strictly spatial: one map per model scenario and only a single map for the period-of-simulation. Each map illustrates, cell-by-cell, the estimated suitability of the modeled scenario conditions for maintaining/restoring the ridge and slough landscape. The map footprint is restricted to the presently remaining portion of the Everglades where ridge and slough landscape was present prior to drainage (**Figure 3-5**).

As the suitability of each subindex was based on its resemblance to predrainage conditions, an estimate of predrainage conditions was needed for each map cell. The available information differed between the subindices. For water depths, the striking

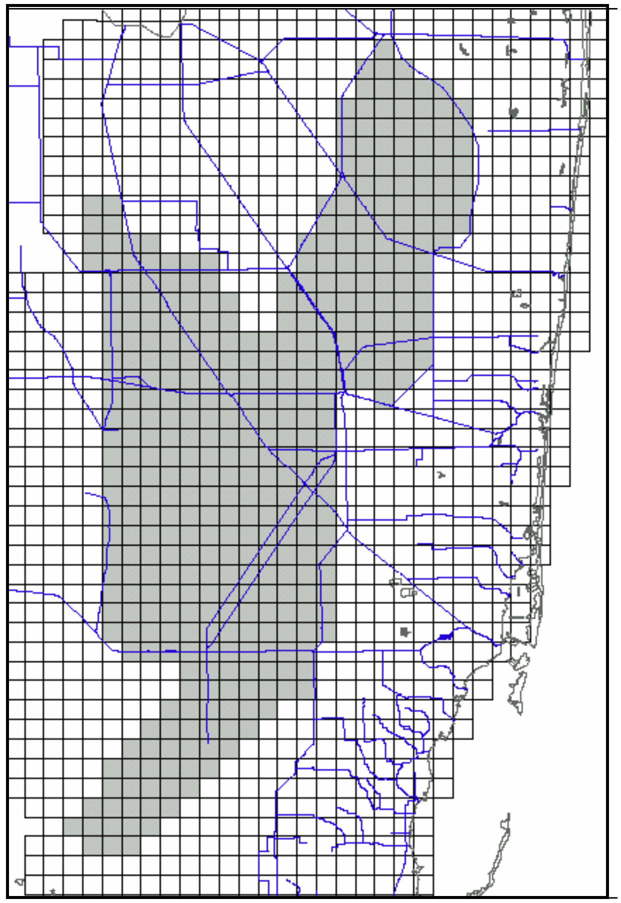


Figure 3-5. SFWMM grid cells applicable for the ridge and slough habitat suitability index.

spatial uniformity of the predrainage landscape pattern (e.g., the reported extreme flatness, the regular spacing of ridges, regular widths of the ridges, similar vegetation in both sloughs and on ridges, etc.) suggests that water depth characteristics were also approximately uniform across the landscape. Estimates for this landscape of predrainage water depths and typical annual variations in water depths were available from an extensive study of historical sources (McVoy et al. in review).

In contrast, for water flows, the same historical study yielded little information on predrainage flow velocities. No formal measurements were uncovered, and the informal ones were too few to extrapolate over time and space. Even if sufficient predrainage flow measurements had been available, it would not have been clear how to convert point velocities, almost certainly measured within sloughs, into spatially-averaged velocities representative of a 2-mile by 2-mile grid cell. A cell of that size typically includes portions of 5 to 6 sloughs and as many ridges. In the absence of measured data, predrainage flow velocities for each grid cell were estimated from Natural System Model version 4.5 (NSM) output.

Predrainage flow directions for each grid cell were estimated from aerial photography, based on the assumption that the directional landscape “grain” formed by the linear sloughs and ridges was identical to the downslope direction and to the direction of predrainage flow. Additionally, as the earliest available photography was flown in 1940, it was necessary to assume that the direction of the grain visible in 1940 was identical to the predrainage direction. This appears reasonable as the primary effect of reduced postdrainage flows was to weaken the original directionality, not to rewrite it in a new direction. **Figure 3-6** shows the ridge and slough directionality mapped from 1940s aerial photos.

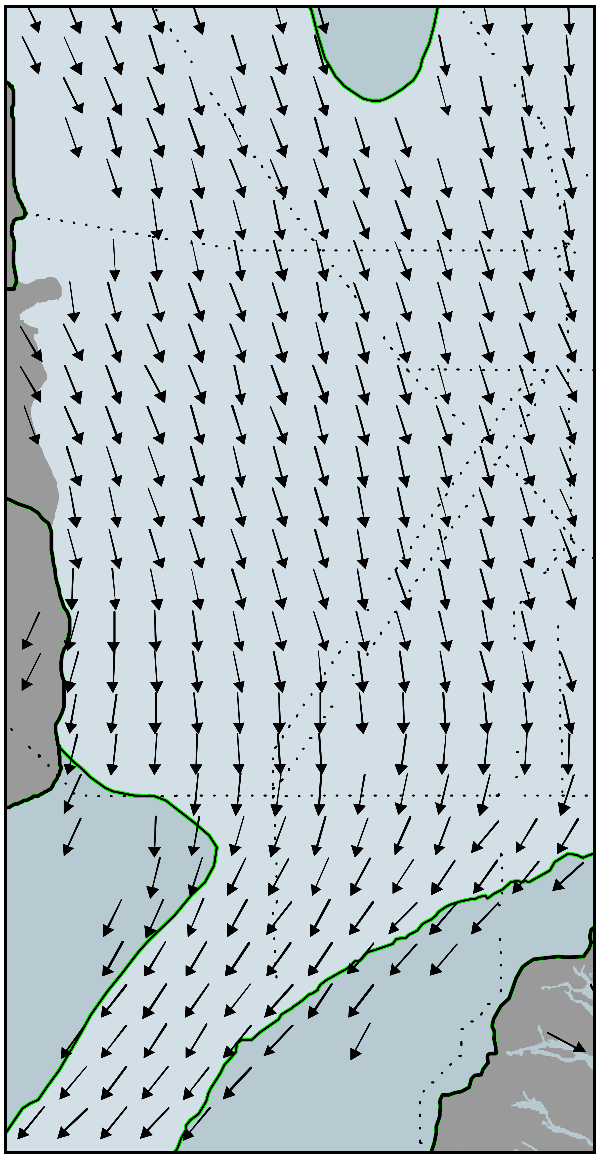


Figure 3-6. Landscape directionality and estimated predrainage flow directions within the western ridge and slough landscape mapped from aerial photographs from 1940. From USDA-SCS (1940), published in Sklar et al. (2001), Figure 2-9. Note continuous flow lines through Water Conservation Areas 3A, 3B and Northeast Shark Slough.

Water Depth Subindex

The form of this subindex is based on 1) the bi-modal nature of this landscape, 2) the assumption that the predrainage elevation difference between a ridge and a slough was about 1.5 feet (45 centimeters) (Wright 1912, Baldwin and Hawker 1915), and 3) the long-standing observation that vegetation in the Everglades is extremely sensitive to water depth (e.g., Harshberger 1914, Davis 1943, Andrews 1957, Loveless 1959, 1960, Sklar et al. 2001). Ridges and sloughs only persisted as such due to the elevation difference between them, and hence their differing water depths. A study in historical ecology (McVoy et al. in review) estimated that predrainage water depths in sloughs ranged, on average, between an annual low of 1 foot (30 centimeters) to an annual high of 3 feet (90 centimeters) resulting in a long-term average of 2 feet (60 centimeters). As the water surface was level across ridges and sloughs, the long-term average water depth on the ridges was 0.5 feet (15 centimeters). Thus, peat soil covered by an average water depth of 0.5 feet will grow sawgrass. If the depth increases to 2 feet, it will turn into a slough. This lability between modes as a function of water depth can be seen in the conditions that have developed at the upstream (shallow) and downstream (deep) ends of the impounded water conservation areas. The upstream end typically turns to pure sawgrass and the downstream end to open sloughs.

These numbers effectively specify a bell-shaped index curve, with an optimum (in terms of slough water depths) at 2 feet, and minima at +/- 1.5 feet relative to the optimum, the lower of which would turn the whole landscape into sawgrass, the higher all into slough. The top axis of **Figure 3-7** shows this relationship. The bottom axis, in units of average grid cell water depth (rather than slough depth), reflects an offset of 0.6 feet. This offset arises from the fact that the average depth in a model grid cell represents a spatially-

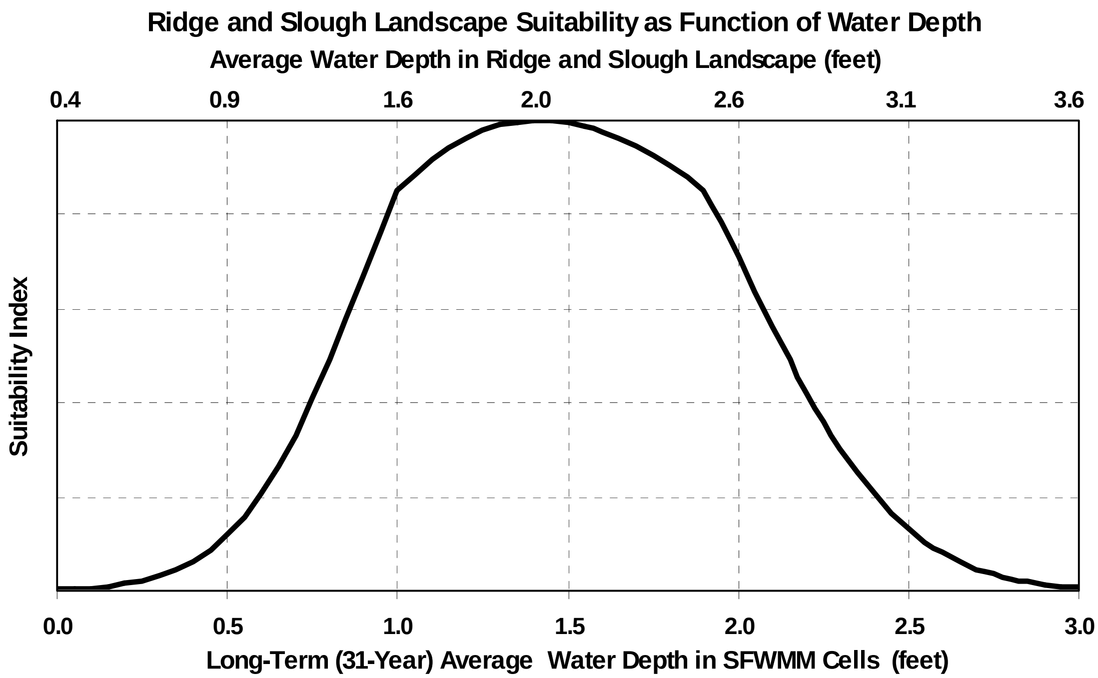


Figure 3-7. Ridge and slough landscape suitability as a function of long-term average water depth.

weighted average of depths on the ridges and depths in the sloughs. Assuming a 1.5-foot land surface elevation difference between ridges and sloughs and a predrainage coverage of 60 percent sloughs and 40 percent ridges, the calculated offset is 0.6 feet. As a minor refinement, the low water side of the bell curve was adjusted slightly closer to the optimum (approximately 0.2 feet) to reflect the assumption that water flow also contributed slightly to counteracting the conversion of sloughs to ridge vegetation under drier conditions.

Water Depth Variation Subindex

Water levels in the predrainage Everglades rose during the course of the wet season and fell during the course of the dry season. Impoundment and other water management practices have altered the amplitude of this annual rise and fall. In some parts of the remaining managed Everglades, water levels vary less than prior to drainage with depths tending to remain too constant. In other areas, the amplitude appears to have increased, now rising higher in the wet season, falling lower in the dry. This increased range is driven by water needs in surrounding areas and is the combined result of the Everglades receiving surplus water during the wet season and being tapped for water supply during the dry season.

For the water depth variation subindex, the difference between the average October water depth (i.e., maximum depth at the end of the wet season) and the average May water depth (i.e., minimum depth at the end of the dry season) for the period of simulation was selected as an indication of the average annual water depth range. An offset of 0.3 feet was added to the water depth range based on October and May average water depths to adjust for the influence of using monthly average water depths rather than daily values (i.e., it was assumed that the annual water depth range calculated from daily values would be 0.3 feet higher than the annual water depth range based on monthly averages since the extremes are lost when averaging into monthly).

A study in historical ecology (McVoy et al. in review) estimated that predrainage water depths typically ranged about 2 feet (60 centimeters) in any given year; that is, the difference between the year's minimum and maximum was 2 feet. For the suitability index, this annual range was assumed to be the optimum for maintenance of the landscape. A bell-shaped curve was assumed, with a maximum at an annual range of 2 feet and a minima when the range was either reduced to zero or increased to 4 feet (**Figure 3-8**). Known requirements of sawgrass growing on the ridges helped set the values of the minima. Sawgrass growing on peat soil is known to thrive best when the annual rise and fall in water levels includes an annual dry period (Davis 1943, Andrews 1957, Forthman 1973, Sklar et al. 2001). An annual range of zero (water level constant) would not achieve this; in fact, since the average water depth was 0.5 feet on sawgrass ridges (**Figure 3-7**) even an annual range of 1 foot (+/- 0.5 feet) would not actually drop the water level below the surface to create a dry period. The zero for the subindex at an annual range of 4 feet is derived both from sawgrass physiology and tree island sensitivity. An annual range as high as 4 feet means that the annual low would be 1.5 feet below surface on the sawgrass ridges and the annual high would be 4 feet about the bottom of the sloughs. Vegetation fires occurred frequently under predrainage conditions, and are harmless to sawgrass

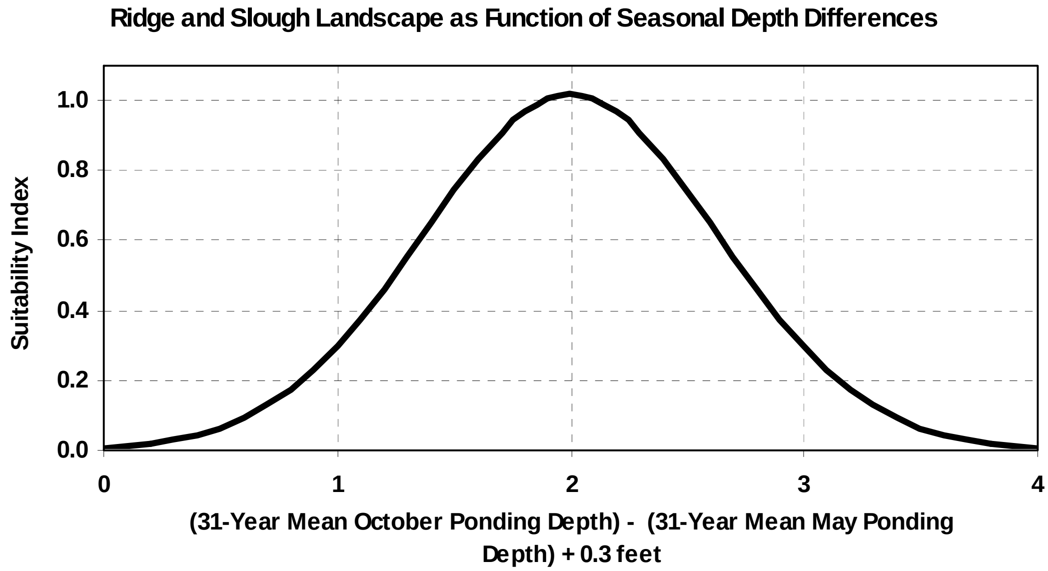


Figure 3-8. Ridge and slough landscape suitability as a function of average seasonal depth differences in the months of May and October.

stands. However, below ground water levels sufficiently low to allow peat fires kill sawgrass stands by burning the culms. All indications are that this did not occur naturally under predrainage conditions. Similarly, the 4 foot annual high that would be associated with an annual range of 4 feet would be high enough to endanger tree island vegetation.

Flow Velocity Subindex

It is widely recognized that water flow, and/or processes related to water flow, have played a role in the formation and maintenance of the ridge and slough landscape (SCT 2003). The linear, spatially-organized pattern of the predrainage system certainly looks like the result of a flow field. Even more powerfully, the postdrainage loss of the predrainage directional pattern, and its replacement by an amorphous, nondirectional pattern, suggests that flow originally exerted some subtle influence that maintained the original pattern. Nevertheless, the processes are not fully understood. Transport of flocculent organic material may play a role, but this has not yet been confirmed experimentally. The relative importance in maintaining the ridge and slough pattern of low energy but continuous processes, versus infrequent but high energy processes has also not been determined.

Despite these limitations, it is important to include a subindex that at least attempts to capture the significance of water flow in this landscape. It is also of some practical reassurance that even though the subindex described here is focused on low energy flows, a favorable suitability map of this index would indicate conditions favorable for unimpeded movement during high energy events as well.

The flow velocity subindex is based simply on the assumption that flow velocities equal to or within +/- 20 percent of predrainage flow velocities would be optimal for maintaining/restoring the landscape (**Figure 3-9**). Velocities lower than one-third

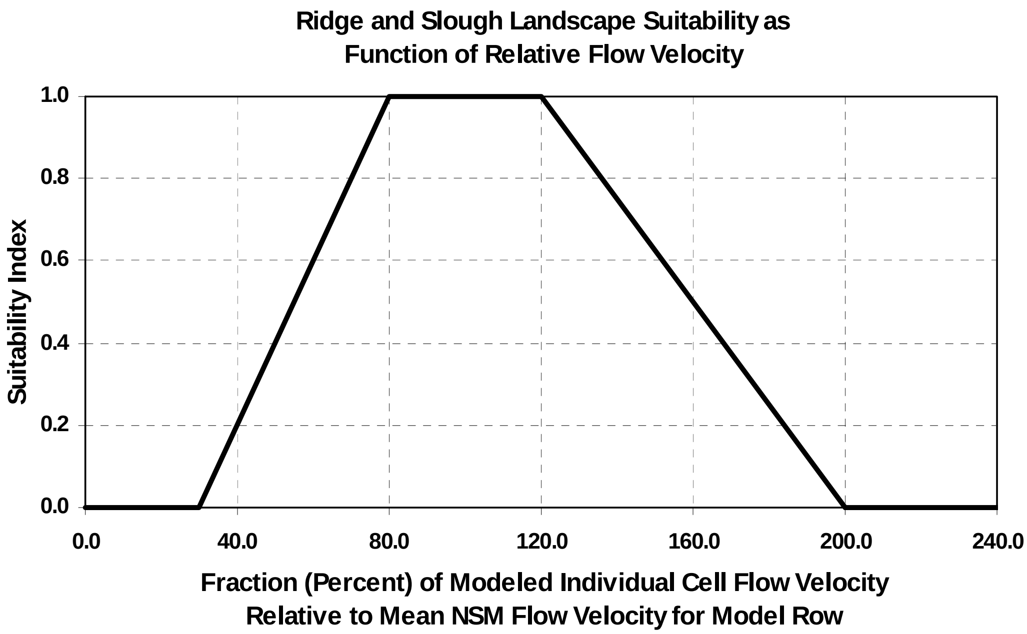


Figure 3-9. Ridge and slough landscape suitability as a function of flow velocity variation from average flow velocity predicted by the NSM.

predrainage or higher than twice predrainage are assumed to have zero suitability. As predrainage flow velocities were not available from the historical record, the grid cell velocities simulated by the NSM were used as a proxy estimate. The uniformity of the predrainage landscape that was discussed in the water depth index would suggest that velocities would also have been quite uniform, and that therefore a single, average velocity calculated from model output for the whole ridge and slough landscape might be most appropriate. The exception to this arises from the approximately three-fold narrowing of the landscape into Shark River Slough, south of the present day Tamiami Trail (U.S. 41). As the landscape pattern itself suggests that predrainage velocities may have increased through this narrowed area, row averages of the model output, rather than a single, whole landscape average velocity were used as proxy estimates of predrainage velocity. Thus, the velocity of each model cell in a given row was compared with the same row average velocity from the NSM.

Flow Direction Subindex

In a patterned peatland where the patterning has been demonstrated to be at once strongly linear under predrainage conditions and subject to degradation into an amorphous pattern under postdrainage conditions, it is logical to assume that the landscape would be best maintained and most likely to be restored if flows occur in line with the original landscape orientation. This is likely to be true regardless of the mechanism that is ultimately found responsible for the link between water flow and landscape pattern. As an example, one can imagine that maintenance of the original pattern in this landscape is dependent upon an unspecified process that occurs in sloughs. If one additionally assumes that ridges and sloughs are in some way different and that the necessary slough process is somehow reduced if water arriving in a slough has passed first through a ridge, then a

substantial sensitivity to the flow direction can be easily imagined. If flow is aligned with the ridges and sloughs, then a substantial fraction of water flowing could pass only through sloughs, without being forced through a ridge. If however the flow field is skewed, the close spacing and long length of the ridges would force water through the ridges, even at a quite small angular deviation from the landscape alignment. Transport of flocculent material through sloughs and filtration of such material by ridges might be example processes that would be sensitive to flow alignment, but other processes can be imagined.

Figure 3-10 illustrates the subindex assumed to represent this sensitivity to flow direction, specifically to the angular deviation between modeled flow direction and the original landscape directionality. Model grid cell-by-grid cell measures of the original directionality were obtained from a separate mapping exercise based on 1940 aerial photographs superimposed on the 2-mile by 2-mile model grid. The assumed steep sensitivity of the subindex to angle (50 percent at 15 degrees) reflects the rationale presented above, and the specific geometry of this landscape.

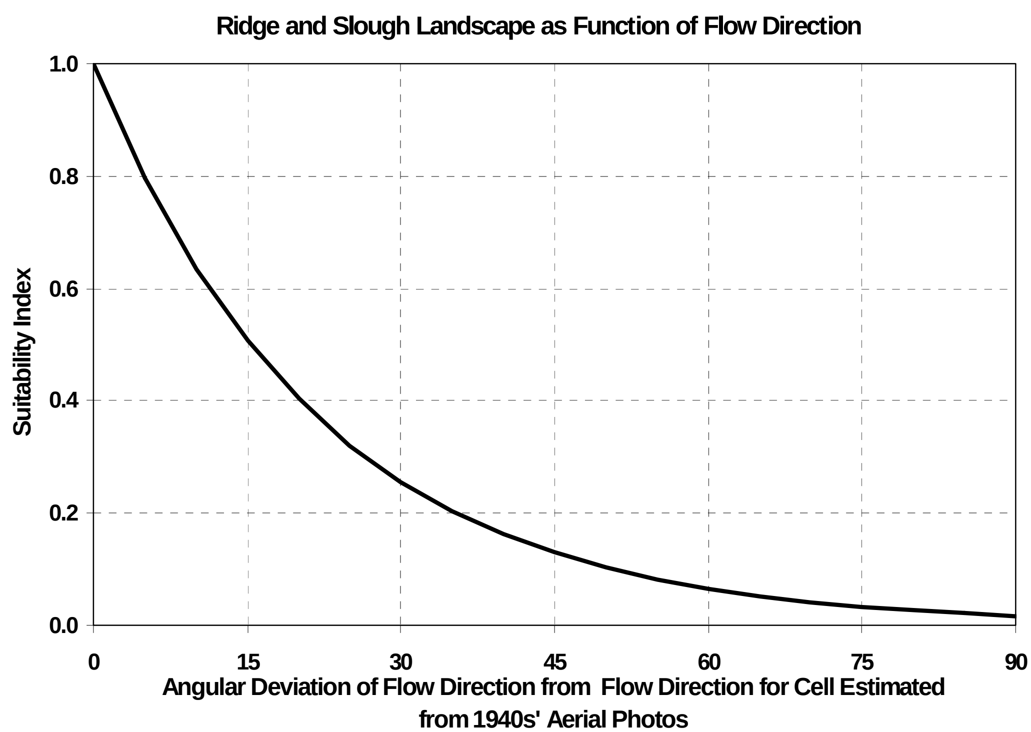


Figure 3-10. Ridge and slough landscape suitability as a function of directional flow variations from historic patterns.

Results

Results of applying the ridge and slough indices to model output from the natural, current, and restored system simulations are discussed for the individual component subindices and then for the overall composite index.

Water Depth Subindex

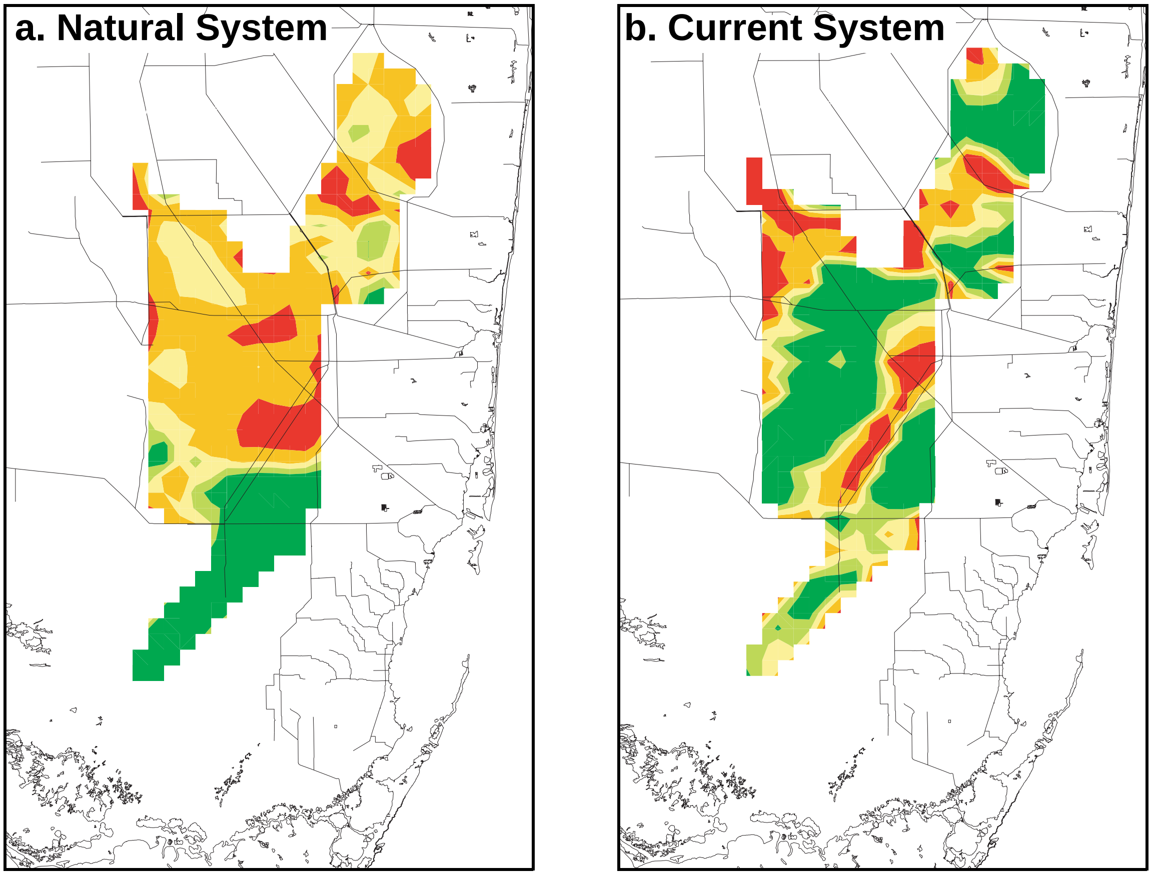
Water depth suitability scores for the natural system simulation (**Figure 3-11a**) are high in Shark River Slough and southern Water Conservation Area (WCA) 3B (> 0.8) and relatively low (< 0.4) for much of the remainder of the ridge and slough landscape. This is surprising since one would expect that in the predrainage Everglades average depths were more suitable for the formation of the ridge and slough landscape throughout the landscape domain. Low water depth suitability in the natural system for large parts of the remaining ridge and slough landscape indicates that the water depth subindex may need to be adjusted. Alternatively, depths simulated with NSM north of Tamiami Trail may not be a good indication of the predrainage water depths responsible for shaping the ridge and slough landscape.

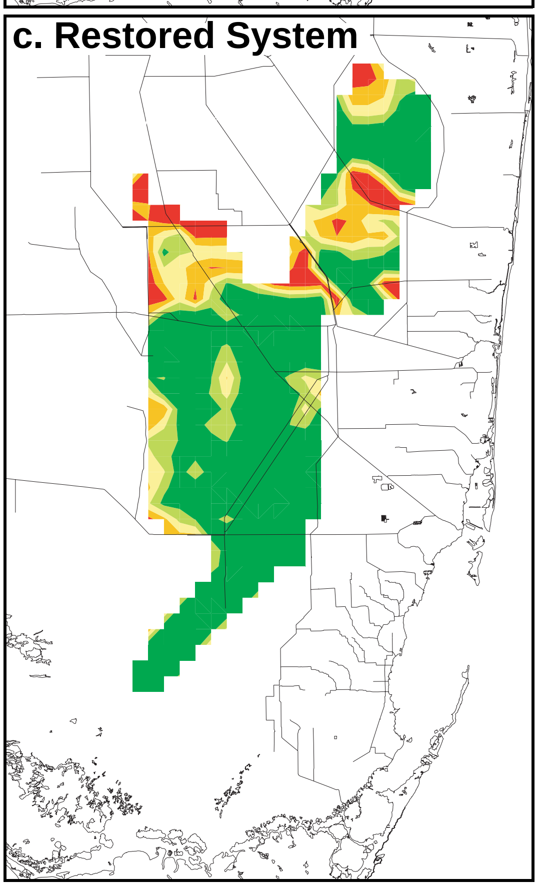
In the current system (**Figure 3-11b**), water depth suitability in Shark River Slough is more marginal (0.4 to 0.8) than in the natural system (**Figure 3-11a**), while water depths for most of WCA 3A are more suitable (> 0.8) than in the natural system simulation. In northwestern WCA 3A and the northern portion of the Arthur R. Marshall Loxahatchee National Wildlife Refuge (LNWR), water depth suitability is low in the current system because average water depths are shallower than the ideal depth defined in the index as suitable for sustaining the ridge and slough landscape. By contrast, in the impounded areas of southern LNWR and in WCA 3A northwest of the L-67 canal, water depth suitability in the current system is low because average water depths are deeper than the ideal depth for sustaining the ridge and slough landscape.

In the restored system (**Figure 3-11c**), average water depths are highly suitable (>0.8) for most of the ridge and slough landscape domain, except in the northern parts of WCA 3A, LNWR, and central WCA 2A where average depths remain shallower than optimal. The extreme southern part of LNWR has poor (0.2) depth suitability with water too deep as in the current system.

Water Depth Variation Subindex

Seasonal depth differences (i.e., wet season average depth minus dry season average depth) in the natural system simulation (**Figure 3-12a**) are suboptimal (< 0.6) for the entire ridge and slough landscape except in Shark River Slough where the seasonal depth suitability index exceeds a value of 0.6. In southern WCA 3B differences in average seasonal water depths are relatively larger and more suitable (> 0.6) than in the remainder of the ridge and slough landscape. Similar to the average water depth index, low seasonal suitability index values over much of the ridge and slough landscape for the natural system suggest that either the index requires adjustment or NSM-simulated depth differences may not be a good indication of the predrainage seasonal water depth differences.





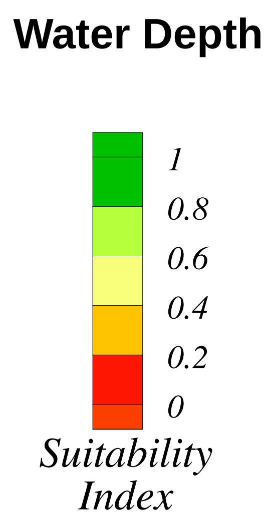


Figure 3-11. Mean annual ridge and slough water depth subindex for a. the natural system, b. the current system, and c. the restored system.

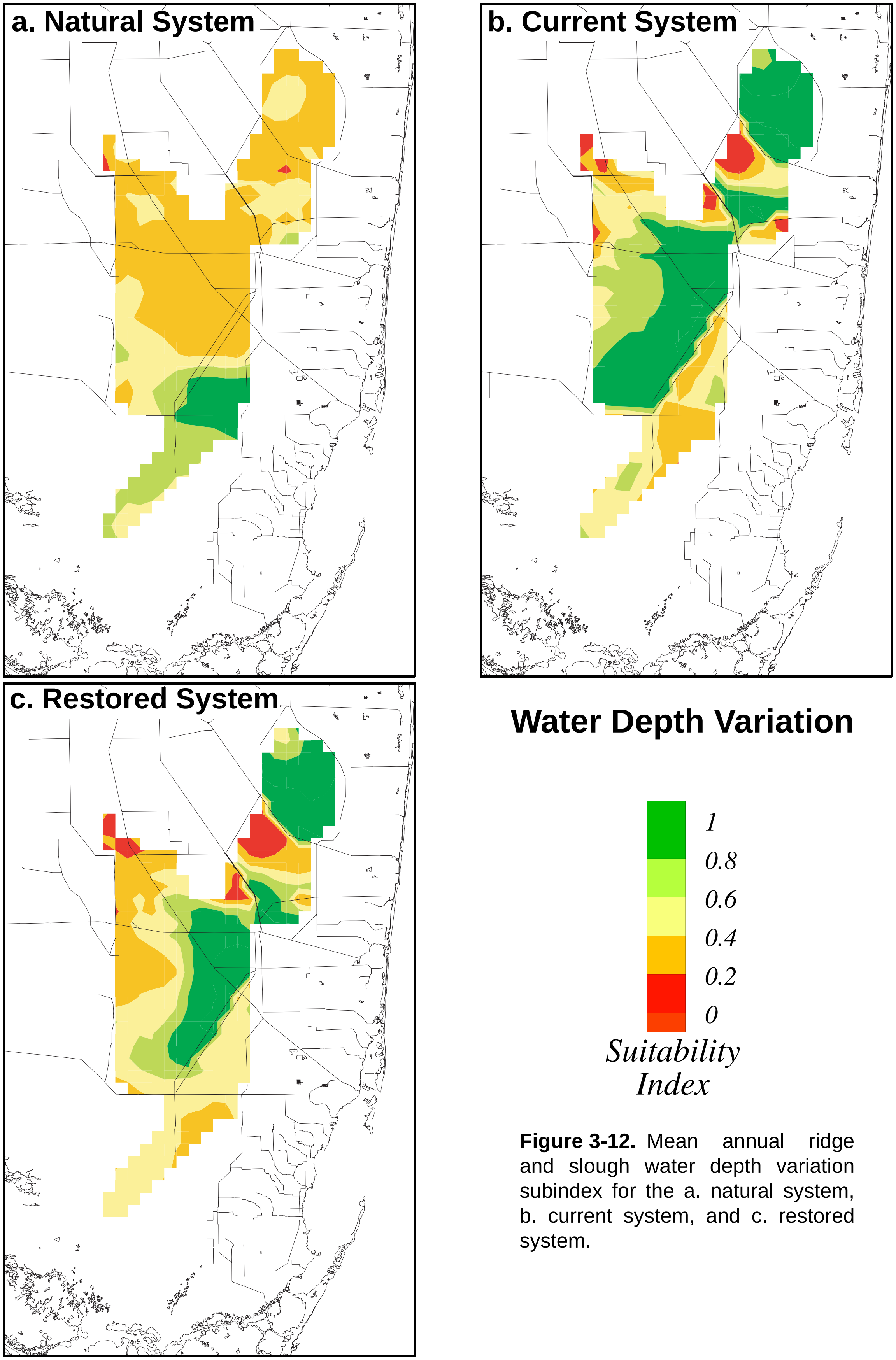


Figure 3-12. Mean annual ridge and slough water depth variation subindex for the a. natural system, b. current system, and c. restored system.

Seasonal water depth differences are more suitable over a much larger area in the current system (**Figure 3-12b**) than in the natural system. Higher suitability (> 0.6) is found in WCA 3A south of Alligator Alley, southern WCA 2A, and LNWR. In northern WCA 3A, northern WCA 2A, WCA 2B, WCA 3B, and Shark River Slough, seasonal water depth differences are less suitable than in the natural system.

In the restored system (**Figure 3-12c**), ridge and slough suitability due to seasonal water depth differences is similar to that of the current system, except that the area of high suitability (> 0.6) does not cover as much of WCA 3A as in the current system. At the same time, the restored system has a relatively smaller area with low suitability (< 0.4) in WCA 3B and Shark River Slough than in the current system.

Flow Velocity Subindex

Figure 3-13a shows very optimal flow velocities (> 0.8) for most of the ridge and slough landscape in the natural system simulation (NSM). The only exception is the southernmost portion of WCA 2A and WCA 2B with suboptimal flow velocities resulting in suitability ranging between 0.2 and 0.6. The very high suitability over most of the ridge and slough landscape in the natural system is due to the fact that the simulated flow velocity for each NSM cell in a given row does not deviate significantly from the average flow velocity for all cells in the row (**Figure 3-14a**), consistent with the assumption that the predrainage flow velocities were quite uniform along approximately east-west transects.

In the current system simulation, optimal flow velocities (> 0.6) are observed in north central WCA 3A and southwestern Shark River Slough (**Figure 3-13b**). Comparison of simulated overland flow vectors for the current system (**Figure 3-14b**) with simulated overland flow vectors for the natural system (**Figure 3-14a**) show very similar flow patterns in these areas with relatively small east-west variability. LNWR, WCA 2B, southern WCA 3B, and northeastern Shark River Slough have suboptimal flow velocities in the current system with suitability ranging from 0.0 to 0.4. In LNWR and WCA 2B, flows have become stagnant after impoundment compared to the natural system. In the natural system, water used to flow unimpeded from WCA 3A, WCA 3B, and the Pennsuco wetlands to northeastern Shark River Slough. The construction of the L-67AC and L-29 (Tamiami Trail) levees and canals has altered the natural flow patterns in the area dramatically. WCA 3B and the Pennsuco wetlands no longer drain into northeastern Shark River Slough. The main source of water for Shark River Slough is now WCA 3A (to the west of the L-67 extension). This has resulted in reduced flows to Shark River Slough.

In the restored system (**Figure 3-13c**), optimal flow velocities (> 0.6) have returned to most of WCA 3A, Shark River Slough, and southwestern WCA 3B (**Figure 3-14c**). The model simulation shows that the decompartmentalization of WCA 3 would result in increased overland flow through WCA 3B into northeastern Shark River Slough. Flow velocities in LNWR, southern WCA 2A, WCA 2B, and eastern WCA 3B are not restored to predrainage values and remain suboptimal (< 0.4).

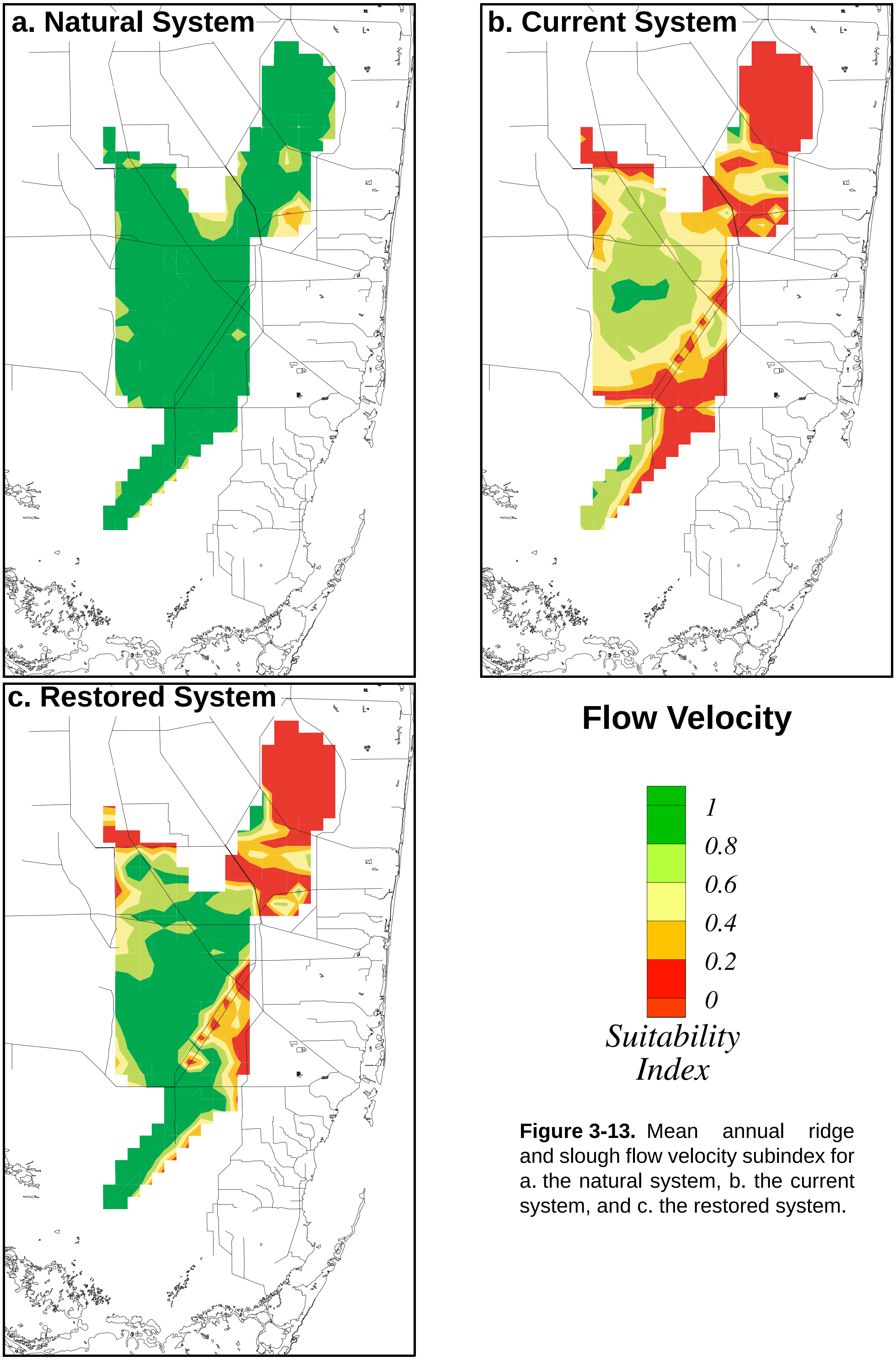


Figure 3-13. Mean annual ridge and slough flow velocity subindex for a. the natural system, b. the current system, and c. the restored system.

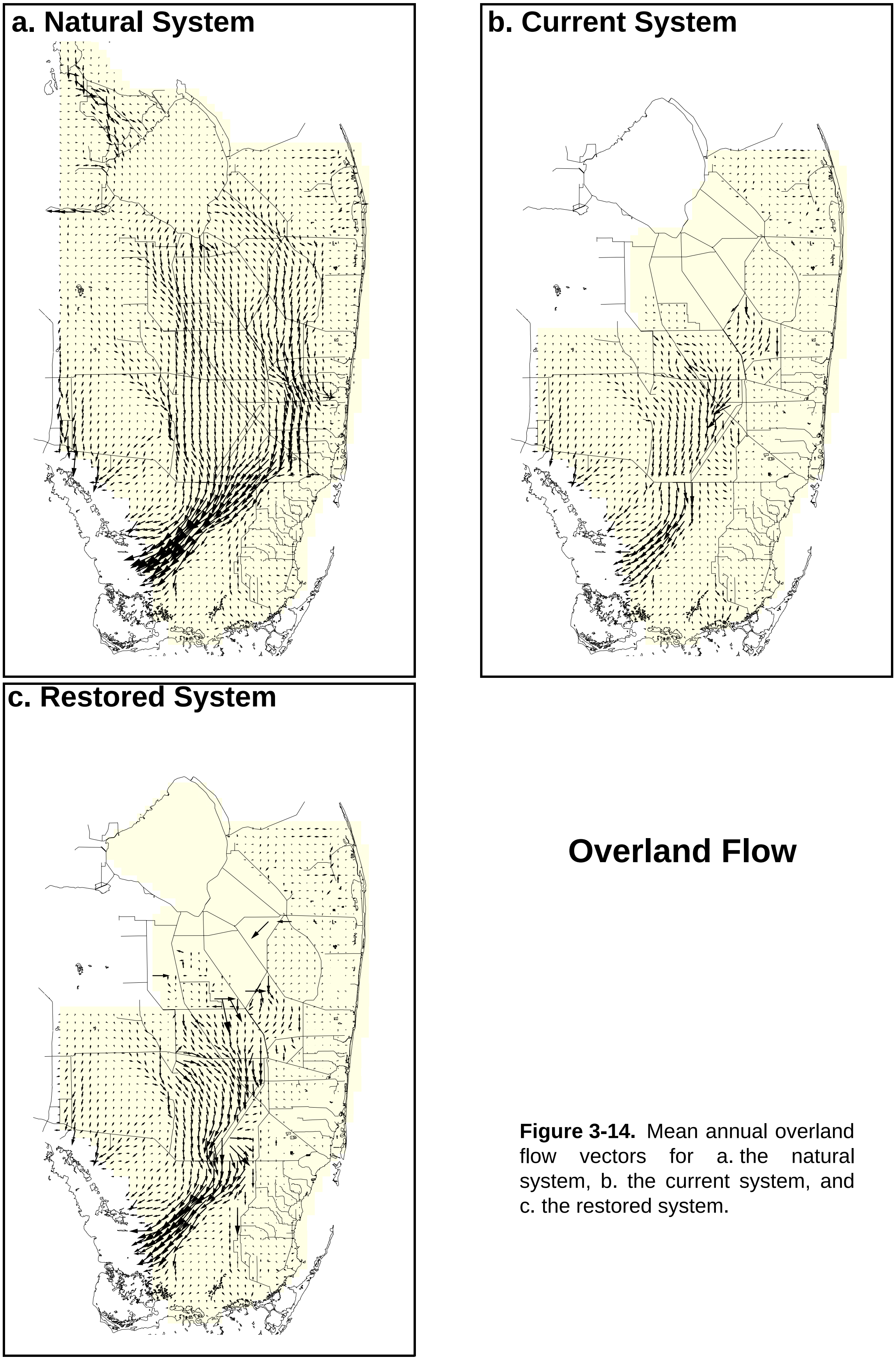


Figure 3-14. Mean annual overland flow vectors for a. the natural system, b. the current system, and c. the restored system.

Flow Direction Subindex

Suitability indicated with the flow direction subindex is very sensitive (possibly oversensitive) to simulated flow direction. Differences between predrainage flow directions estimated from 1940s' areal photography (**Figure 3-6**) and predrainage flow directions estimated in the NSM (**Figure 3-15a**) are pronounced in WCA 3B, the southwestern corner of WCA 3A, and to a lesser extent a strip across central LNWR.

Flow direction differences between the NSM simulation and the predrainage flow direction indicated by 1940s photography may be caused by some influences of current topography in the NSM simulation. Flow shifts from predominantly north to south to the southwest in a strip across central LNWR. Low flow direction suitability subindex values in WCA 3B (< 0.4) highlight two possible interpretations of the predrainage flow pattern. NSM indicates a general southwesterly flow in WCA 3B while the 1940s' photo interpretation indicates flow directions may have been more southerly.

In the current system, the flow direction subindex indicates that directionality of flow may have been lost for most of the remnant Everglades (**Figure 3-15b**). The only areas where flow direction is still consistent with the estimated predrainage flow directions are in some parts of WCA 3A and southeastern Shark River Slough.

Flow directionality, according to the flow direction subindex, improves for large parts of WCA 3A and Shark River Slough in the restored system (**Figure 3-15c**) compared to the current system (**Figure 3-15b**). Partial decompartmentalization between WCA 3A and WCA 3B in the restored system does not improve flow directionality within WCA 3B, and continued impoundment of water in LNWR, WCA 2A, and WCA 2B result in continued poor flow direction suitability in these areas.

It is possible that the flow directionality subindex is too stringent. A 15 degree angular variation in flow direction reduces flow direction suitability to a value of 0.5 (**Figure 3-10**). Since the decline in suitability relative to flow direction indicated in **Figure 3-10** is hypothetical, more information and different hypotheses will result in adjustment of the shape of the flow directionality index. The importance of quantifying and producing the flow directionality suitability index is that results of different hypotheses can be visualized and further evaluated relative to other indices and the latest state of knowledge.

Overall Ridge and Slough Suitability

For the natural system, the overall ridge and slough suitability is lower than would be expected for predrainage conditions. Ridge and slough suitability ranges between 0.4 and 0.6 for most of the remnant Everglades with parts of western LNWR, northern WCA 2A, and northern WCA 3B with suitability between 0.2 and 0.4 (**Figure 3-16a**). Small parts of WCA 2A, northeastern WCA 3A, and a swath from southern WCA 3A through southwest WCA 3B and into Shark River Slough have ridge and slough suitability greater than 0.6. Only in Shark River Slough and a tongue up into WCA 3A is ridge and slough suitability between 0.8 and 1.0.

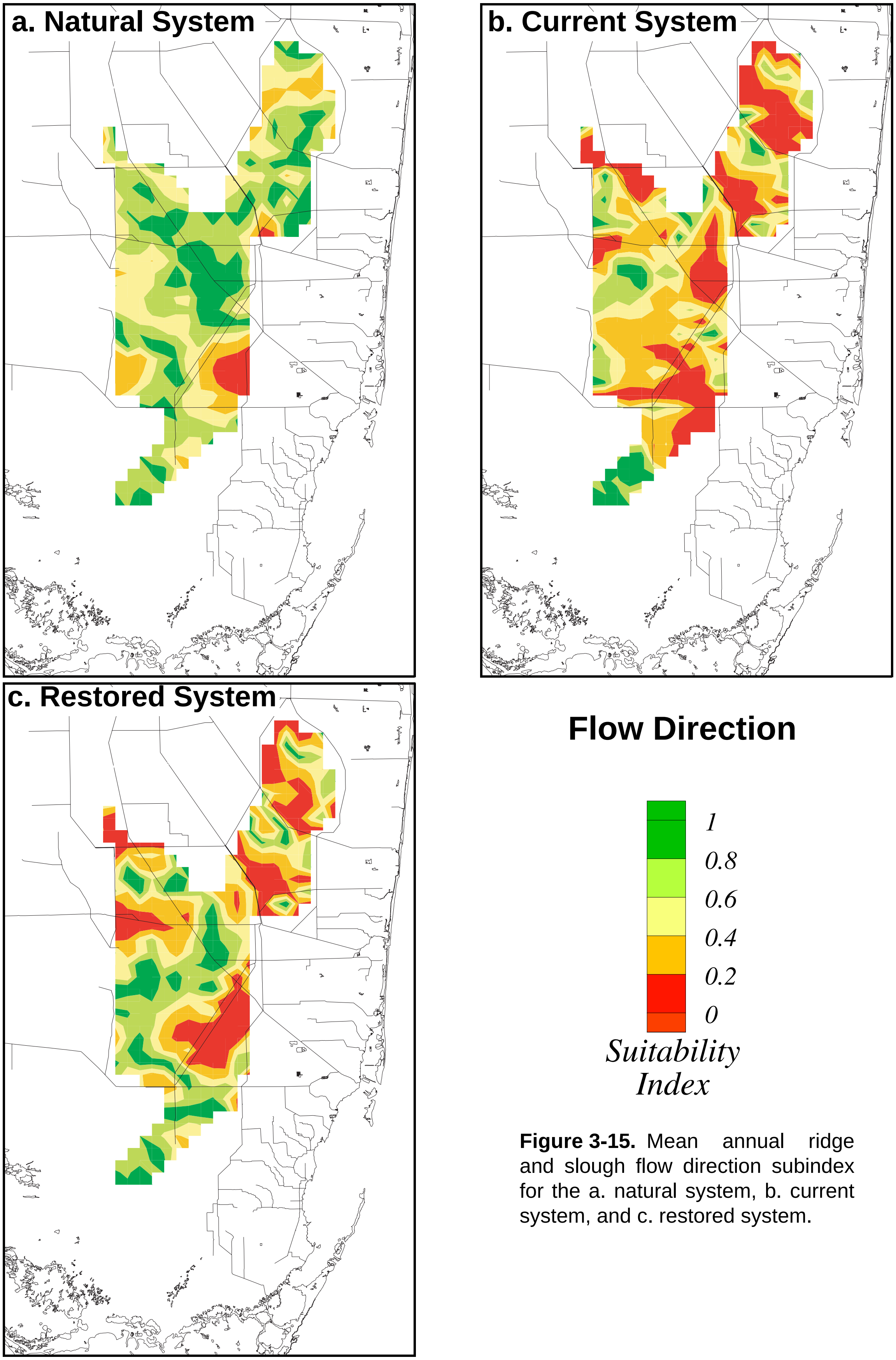
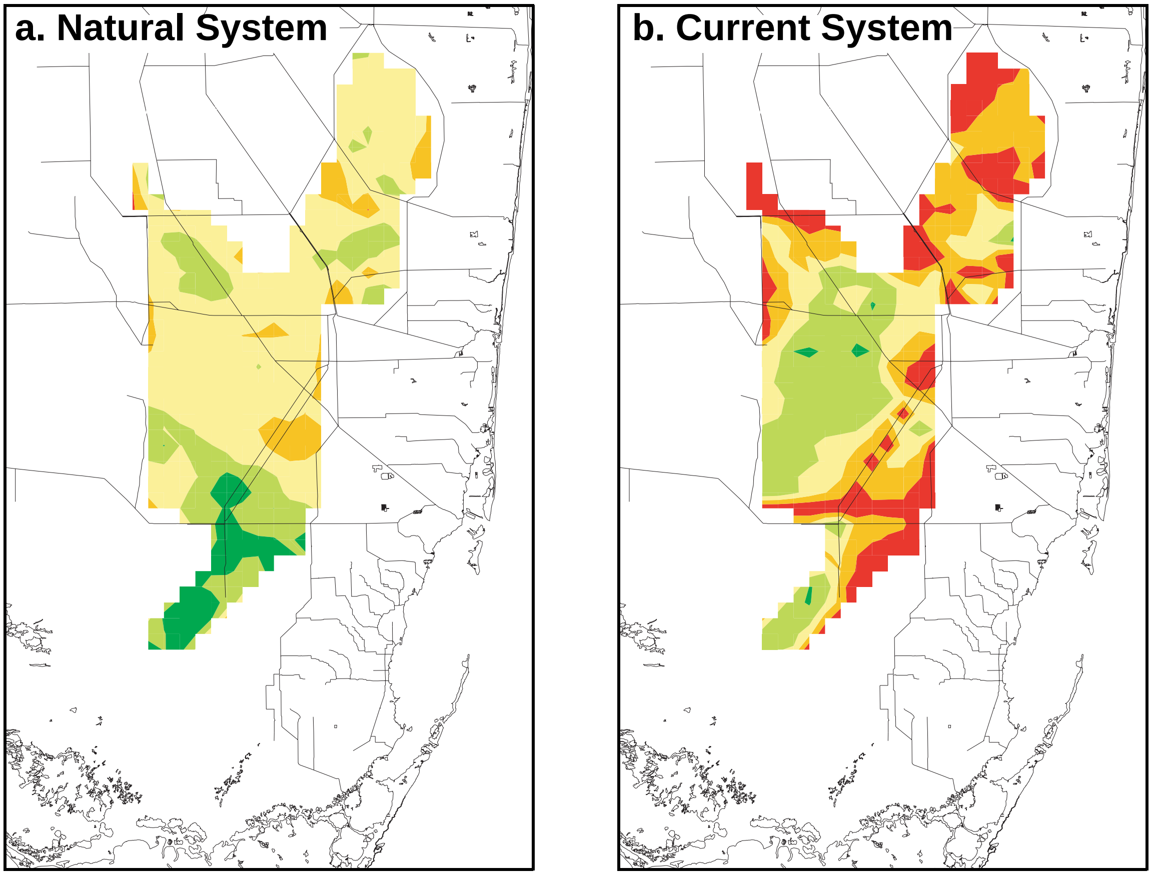
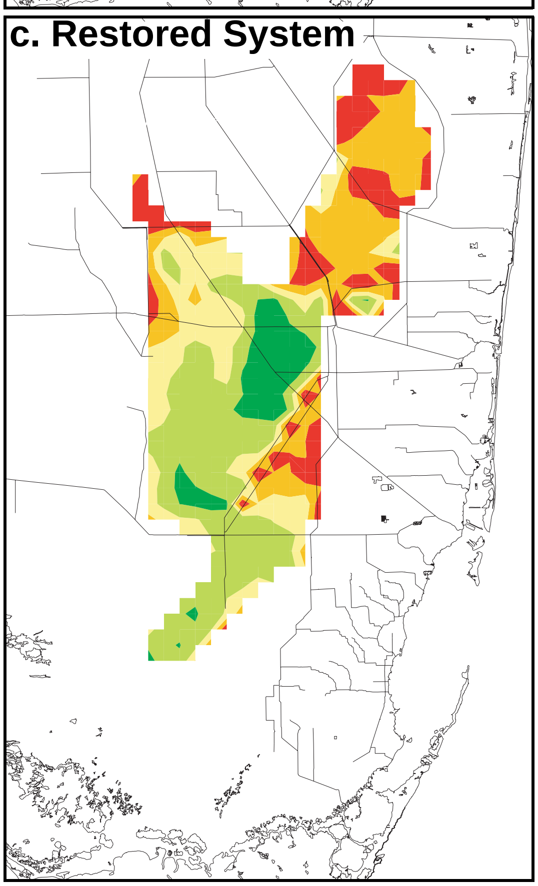


Figure 3-15. Mean annual ridge and slough flow direction subindex for the a. natural system, b. current system, and c. restored system.





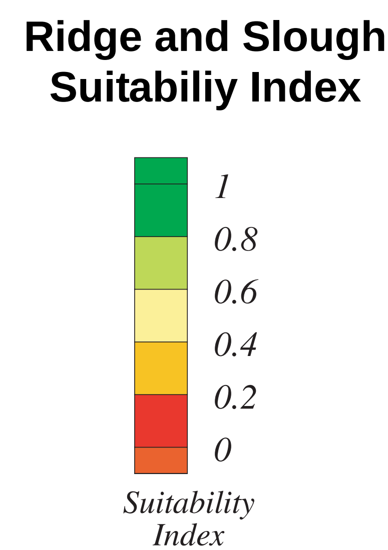


Figure 3-16. Mean annual ridge and slough composite suitability index for the a. natural system, b. current system, and c. restored system.

The previous section indicated that the flow direction suitability subindex may be too stringent. In the next section, the ridge and slough depth subindex is investigated though sensitivity analysis. Poor ridge and slough suitability for large parts of the simulated natural system suggest that several of the ridge and slough subindices may require further refinement. Alternatively, the NSM may not adequately represent the predrainage hydrology that was ideal for ridge and slough development and it too may require refinement.

Ridge and slough suitability in the current system ranges from poor (< 0.4) throughout LNWR, in northwestern WCA 2A, WCA 2B, northwestern WCA 3A, most of WCA 3B, and northeastern Shark River Slough (**Figure 3-16b**). Ridge and slough suitability exceeds 0.6 for most of central WCA 3A and southwestern Shark River Slough.

In the restored system (**Figure 3-16c**), the area more suitable (> 0.6) for ridge and slough formation extends from north of Alligator Alley in WCA 3A south through most of WCA 3A and down into Shark River Slough. WCA 3B still has poor ridge and slough suitability (< 0.4), as do LNWR, WCA 2A, and WCA 2B.

Sensitivity to Water Depth Subindex Definition

Sensitivity analysis permits investigation of the robustness of a particular habitat suitability function by modifying the function systematically and comparing the results using the modified function against results of the original function and also best knowledge of the systems represented by the functions. Sensitivity of the ridge and slough landscape to water depth was analyzed by shifting the optimal water depths from 2 feet (**Figure 3-17**) down in quarter-foot increments to 1.75 feet and 1.50 feet and up a quarter of a foot to 2.25 feet for both the natural and current system simulations. The shape of the ridge and slough suitability function for the water depth subindex was assumed to stay the same, and shift as the optimal depth was shifted.

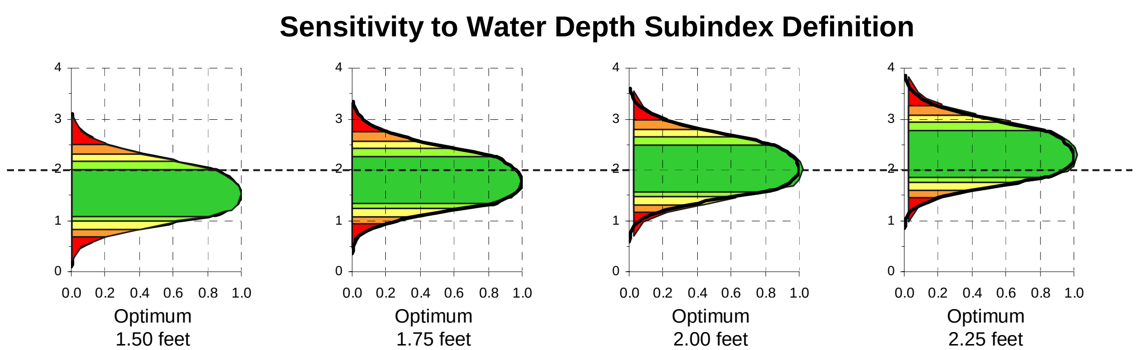


Figure 3-17. Variations in the water depth subindex definition for sensitivity analysis.

The ridge and slough sensitivity analysis for the natural system is shown in **Figure 3-18**. As was discussed previously for the natural system, an optimal depth of 2.0 feet results in high suitability for the ridge and slough landscape in Shark River Slough and lower suitability over much of the remaining ridge and slough landscape. Shifting the optimal depth to 1.75 feet results in a much larger portion of the ridge and slough landscape with high depth suitability. Further reducing the optimal depth to 1.50 feet results in most of the domain having close to ideal (0.8 to 1.0) depth suitability. An exception is Shark River Slough, where suitability is lower as deeper water in this area starts to indicate lower suitability as the suitability index is shifted down. Increasing the optimal depth to 2.25 feet results in most of the domain having low suitability (< 0.2) because it is too shallow. This sensitivity analysis for the natural system simulation tends to indicate that a lower optimum depth (possibly 1.75 feet) may be more appropriate for the ridge and slough landscape suitability index, since it would be expected that a reasonably large portion of the landscape would have had depths suitable for the formation of the ridge and slough landscape under natural conditions.

Results of the sensitivity analysis for the current system are shown in **Figure 3-19**. The 2.00-foot optimal depth results in high ridge and slough landscape suitability over much of WCA 3A, WCA3B, and LNWR with slightly lower suitability in Shark River Slough. Along the L-67 canal, suitability is low because it is deeper than optimal and, in the northwestern parts of WCA-3A and WCA 2A, suitability is low because it is shallower than optimal. As optimal depths are shifted to 1.75 feet and then to 1.50 feet, the area of low suitability along the L-67 canal (due to deeper than optimal depths) expands while the areas with shallower than optimal depths shrink. Current knowledge of the extent of the area of WCA 3A to the northwest of the L-67 canal that has been impacted by high water could be used with this sensitivity analysis to provide more information on whether an optimal ridge and slough depth of 1.50 or 1.75 feet may be more appropriate than that of 2.00 feet. Increasing the optimal depth to 2.25 feet in the current system reduces the area of low suitability along the L-67 canal, but results in lower suitability in Shark River Slough and larger portions of northwestern WCA 3A and WCA 2A.

The ridge and slough depth subindex is relatively sensitive to shifts of the optimal depth in quarter-foot increments. Both the natural and current system simulations tend to indicate that a lower optimal depth may be more appropriate for the ridge and slough suitability index.

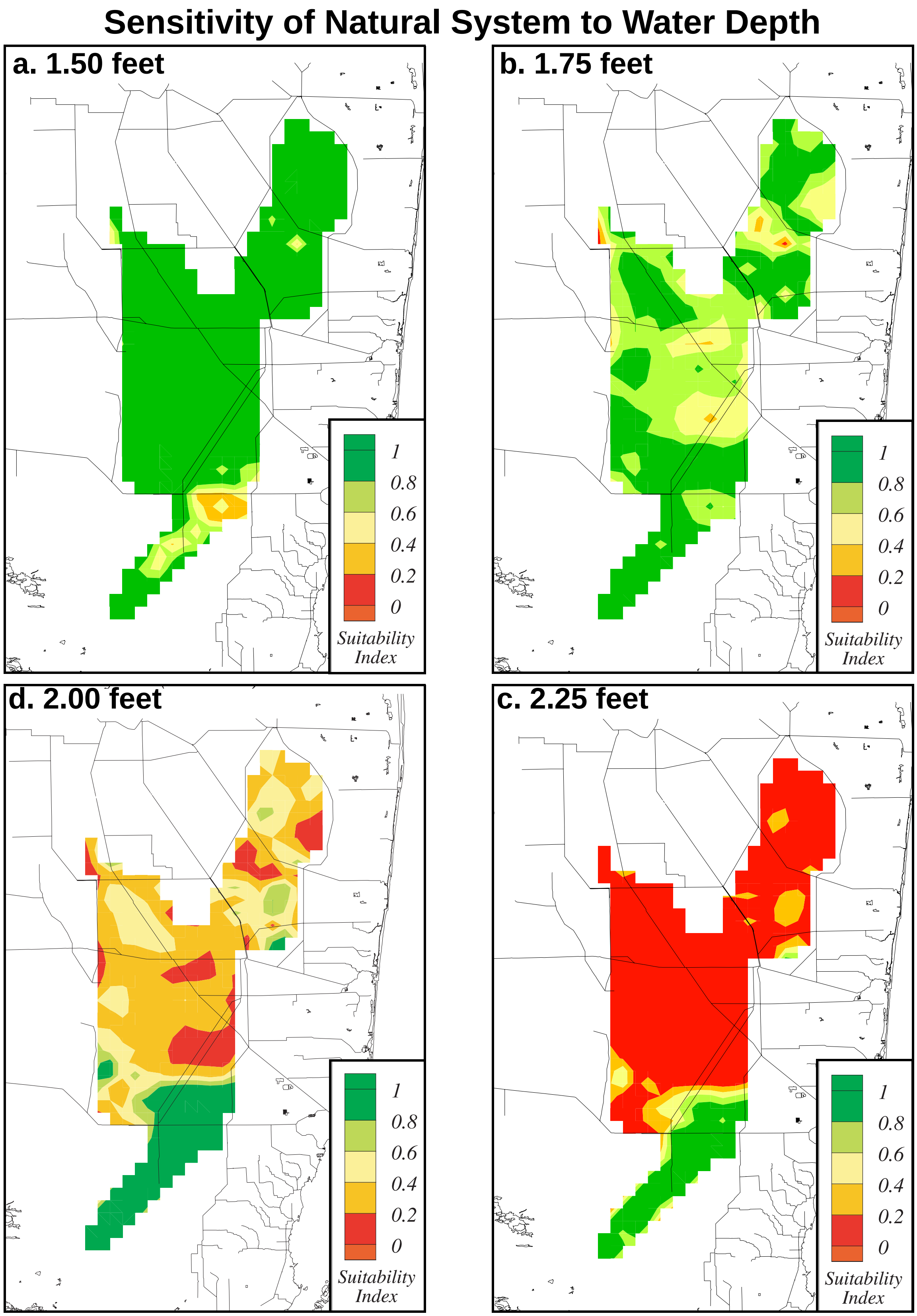


Figure 3-18. Sensitivity of the ridge and slough to alternative definitions of the water depth subindex for the current system with optimums of a. 1.50 feet, b. 1.75 feet, c. 2.00 feet, and d. 2.25 feet.

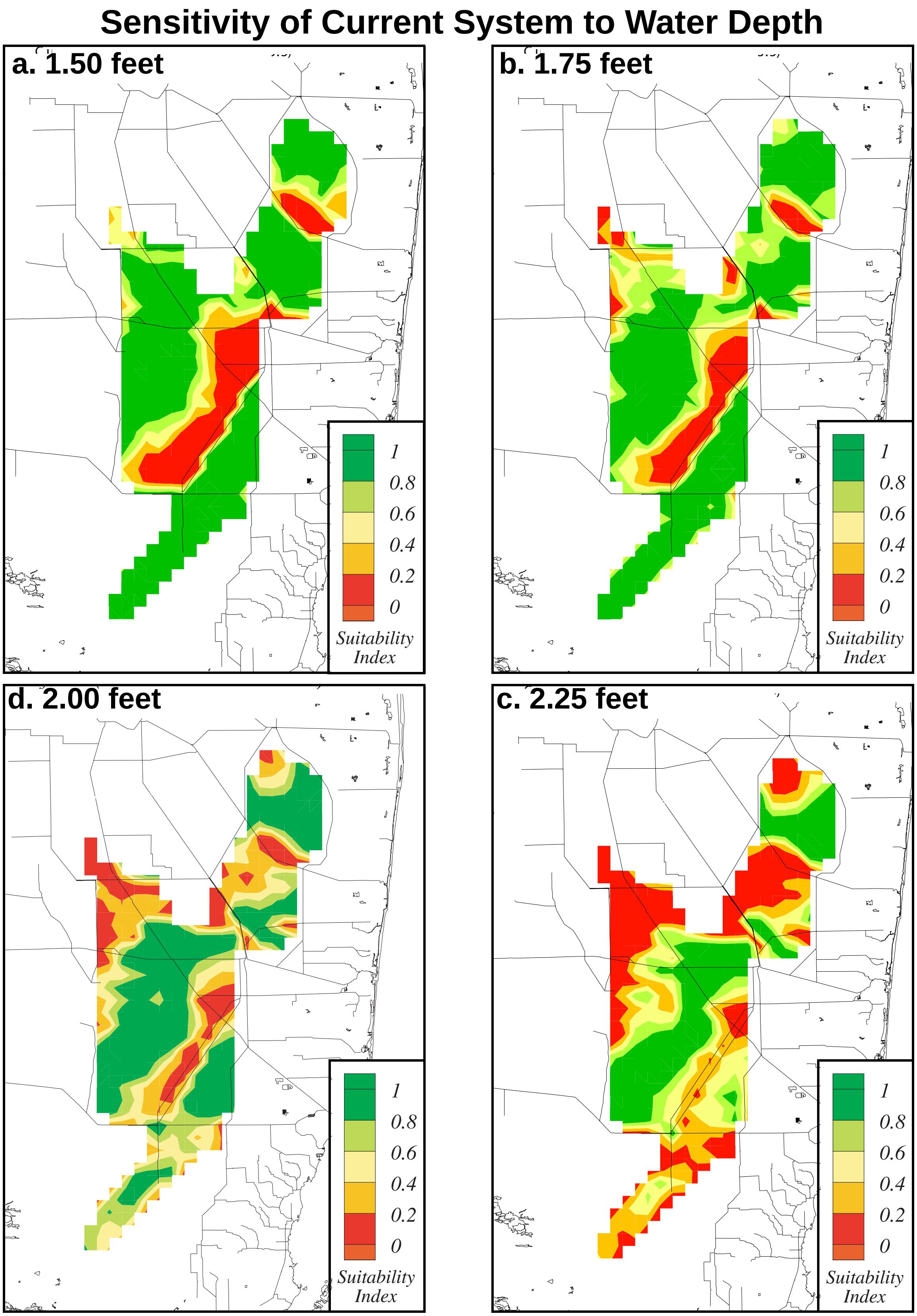


Figure 3-19. Sensitivity of the ridge and slough to alternative definitions of the water depth subindex for the current system with optimums of a. 1.50 feet, b. 1.75 feet, c. 2.00 feet, and d. 2.25 feet.

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CHAPTER 4

Tree Island Habitat Suitability Index

I. Lorraine Heisler[1], Yegang Wu[2], Fred H. Sklar[2], and Kenneth C. Tarboton[2]

General Description

Tree islands, such as those shown in **Figure 4-1**, are a unique and important component of the Everglades landscape (Loveless 1959, Dineen 1974, Zaffke 1983, Sklar and van der Valk 2002). Tree islands support high plant species diversity, provide nesting habitat for a variety of wetland reptiles and birds, and serve as wet-season refuges for upland animals such as white-tailed deer (Loveless and Ligas 1959). Although the total area of all tree islands combined may be only 5 to 10 percent of the Everglades (Schneider 1966), this small portion of the landscape supports more species of birds and animals than any other habitat (Gawlik and Rocque 1998).

Figure 4-1. Tree islands in the ridge and slough landscape of the Everglades.

1. United States Fish and Wildlife Service, South Florida Field Office

2. South Florida Water Management District

Tree islands are complex and diverse forest ecosystems that comprise a variety of plant communities associated with different hydroperiods, climatic regions, soils, and salinities (Armentano et al. 2002). Island topographical highs are usually 1.0 to 3.0 feet higher than the surrounding wetlands (Loveless 1959), although some islands rise as much as 5.0 feet or more above the marsh (Heisler et al. 2002). Surface elevation slopes are extremely gradual and are associated with gradients in vegetation, especially along the long axis of the many teardrop shaped islands. Relatively small changes in water depths and durations can thus produce distinct shifts in island hydroperiods, which in turn alter the vegetation communities that the island can support (McPherson 1973). Vegetation shifts may also occur without changes in water depth if island elevation is lowered as a result of soil oxidation (Loveless 1959). Although the size of tree islands can range from less than one acre to as large as a several hundred acres, the proportion of an island that is relatively elevated (i.e., more than 1.5 feet above the surrounding marsh) is typically less than 0.25 acres (Heisler et al. 2002). Thus changes in water depth may profoundly affect the spatial extent of the shorter hydroperiod, drier portions of tree islands that provide scarce habitat for hammock plants and terrestrial animals.

Tree islands in the central Everglades have been dramatically altered by hydrologic changes during the past century. Drought, fire, and prolonged flooding of islands have been reported to be the principal sources of damage to island vegetation and soils (Loveless 1959, Dineen 1972, McPherson 1973, Schortemeyer 1980, Guerra 1996). In Water Conservation Area (WCA) 2A, more than 85 percent of islands were reported to have disappeared during high water conditions that occurred between 1965 and 1970 (Dineen 1974, Wu et al. 2002). In WCA 3A and WCA 3B, the spatial extent of tree islands decreased by more than 60 percent between 1940 and 1995 (Sklar and van der Valk 2002).

Restoration of degraded tree islands and protection of intact islands are among the goals for restoration of the Everglades ridge and slough ecosystem. Current restoration plans predict dramatic changes in depth patterns over portions of the ridge and slough landscape that have large numbers of tree islands. Therefore, performance measures based on currently available data and analysis are needed to evaluate the effects of proposed hydrologic changes on island ecology, topography, and spatial extent.

Hydrologic Variables

Hydrologic variables considered influential in maintaining tree island habitat include threshold high and low depths tied to durations above or below these thresholds. Tree island habitat suitability indices focus on effects of hydrology on hardwood hammocks and elevated portions of bayhead tree islands in the ridge and slough region. The rationale for this is that if the hydrologic conditions needed to support hammock communities on the highest tree islands are restored, in conjunction with restoration of marsh depth patterns that will maintain sawgrass ridge and slough communities, then the overall hydropattern should implicitly include conditions that would support the full range of tree island vegetation types, from the most to the least hydric, at appropriate elevations and locations within the landscape.

Simulation results from the Everglades Landscape Vegetation Model (ELVM) have suggested that duration of island inundation is a major factor contributing to tree island development and stability in the Everglades. Landscape models by Wu et al. (2002) have shown that patterns of loss of spatial extent of tree islands in WCA 2A and WCA 3A can be approximated using models that focus on the depth and duration of island flooding across the landscape.

Fire is a natural process in the Everglades. However, drainage and impoundment of the Everglades during the past century has increased the duration of dry periods and the frequency, intensity, and spatial extent of fire. This has led to extensive loss of peat soils both in the marshes and on tree islands, as well as to destruction of tree island vegetation (Loveless 1959, Schortemeyer 1980). Schortemeyer (1980) estimated that by the 1980s, tree islands in northern WCA 3A had lost as much as 95 percent of their soil volume at low-to-intermediate elevations.

In addition to the impact of intense fires on soils and tree island vegetation, soil loss has altered the topography of the Everglades. Peat-consuming fires and oxidation have caused widespread surface subsidence throughout the ridge and slough landscape (Stober et al. 1998). It is not presently known whether tree islands and marshes have lost soil at similar or different rates, but recent work suggests that overdrained areas of the Everglades have suffered a reduction in topographic heterogeneity, including a reduction in the depth of sloughs that would serve as natural fire breaks (SCT 2003). Oxidized soils also become enriched in nutrients, which can promote the spread of cattail monocultures and other vegetation changes.

Two specific hydrologic variables were selected to serve as general indicators of prolonged low and high water conditions. These variables were chosen because they were found to be good statistical predictors of tree island species richness (Heisler et al. 2002). The indicator for prolonged low water conditions was the percent of time that ground water receded more than 1.0 feet below model grid cell ground surface. The indicator for prolonged high water conditions was the percent of time that depths exceeded 2.0 feet above model grid cell ground surface. This benchmark was chosen on the following rationale. Because tree islands vary in elevation, no single depth/duration measure can indicate the same intensity of flooding for all islands. However, a common benchmark is required if model output is to be evaluated across the ridge and slough landscape.

Habitat Suitability Functions for Tree Islands

The habitat suitability indices presented here are founded on different theoretical rationales and use different types of supporting information. The first index, a species richness suitability index, employs a measure derived from statistical analysis of vegetation and hydrologic data for tree islands in WCA 3A. The Natural System Model version 4.5 (NSM) is then used to identify hydrologic targets for this measure (SFWMD 1998). The second index, a tree island suitability index is based on simple dynamic models of tree island stress and recovery, using parameters derived from the published literature, field observations, and landscape vegetation models (Wu et al. 1996, 1997,

2002). Tree island suitability functions were developed based on hydrologic parameters for the 2-mile by 2-mile grid cells of the South Florida Water Management Model (SFWMM) and the NSM and applied to grid cells for the ridge and slough landscape (**Figure 4-2**), which is the area within which tree islands predominantly occur.

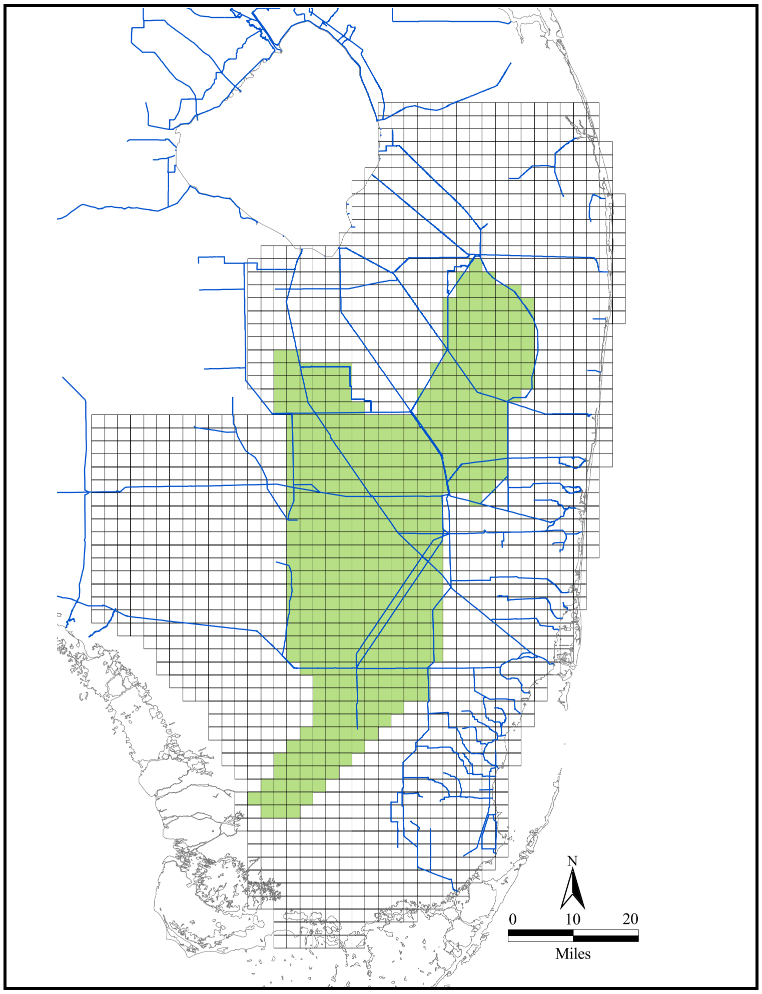

Figure 4-2. SFWMM grid cells applicable for the tree island habitat suitability index.

Species Richness Suitability Index

The species richness suitability index (SRSI) is based on a statistical relationship between estimated hydrologic conditions during 1979 to 1995 and field data from 1997 to 1999 on tree island vegetation on hammocks and elevated bayheads in WCA 3A. The approach to defining the index entailed two steps. First, regression analysis was used to develop a predictive equation relating hydrologic model output to field-collected data on tree island vegetation. The regression equation defined an aggregate hydrologic variable that combines and weighs its component measures in a manner that best explains observed variance in tree island vegetation condition. The second step involved rescaling this variable into a suitability index that measures how well a given water management

scenario matches predrainage hydrology for this measure, using estimates provided by the NSM (SFWMD 1998).

A number of statistically significant associations between hydrology and vegetation were identified, including hydrologic predictors of species richness, vegetation cover, and island spatial extent (Heisler et al. 2002); however, one vegetation variable stood out in the analysis: the number of tree and shrub species observed in vegetation transects exhibited both the largest proportion of variance explained by hydrologic variables and a statistically significant negative association with both the frequency of extreme low ground water conditions and the frequency of island flooding. This result confirmed and extended earlier inferences based on eyewitness observations (e.g., Loveless 1959, Guerra 1996) and smaller field studies (e.g., McPherson 1973, Dineen 1974) that prolonged drought and prolonged high water conditions are both causes of damage to tree island vegetation in the Everglades water conservation areas.

Heisler et al. (2002) reported that the statistically best predictor of the relationship between high water conditions and species richness was the percent of weeks during 1979-1995 in which islands in WCA 3A were estimated to have been flooded within 1.0 feet of their maximum elevation. Their analysis was based on species richness data from a sample comprised of the highest island in each of 22 SFWMM grid cells, and these islands averaged approximately 3.0 feet in maximum height. Thus, 2.0 feet corresponds to a depth above which the highest islands in a representative sample of WCA 3A grid cells would be flooded to a degree that predicts a reduction in species richness. Note that the measure does not imply that *any* depths over 2.0 feet are damaging, only that the cumulative effects of longer durations above 2.0 feet appear to be so. Using the above hydrologic indicators, a score for predicted species richness (PSR) is defined as follows:

$$PSR = 13.4 - 0.75(LO\%) - 0.10(HI\%)$$

where LO% is the percent of weeks in the simulation period with mean weekly depth less than -1.0 feet and HI% is the percent of weeks with mean weekly depth greater than 2.0 feet.

PSR thus provides a measure of the decrease in the number of tree and shrub species, relative to a maximum of 13.4, that would be predicted to occur on a hypothetical 3.0-foot high tree island in the model cell in question. Note that PSR should be constrained to a minimum value of zero; however, negative values for PSR have not yet been obtained using SFWMM or NSM (SFWMD 1998, 1999) output for ridge and slough model cells.

Figure 4-3 illustrates the degree to which PSR predicts observed species richness on tree islands in WCA 3A and 3B. PSR appears to predict observed values fairly well for islands in the range of 2.5 to 3.5-foot maximum elevation. PSR is less accurate in predicting species richness on higher or lower islands. This suggests that the flooding depth criterion of 2.0 feet is appropriate as an indicator of flood stress to “typical” elevated islands, but may not be as good a tool for evaluating potential hydrologic impacts to higher or lower tree islands.

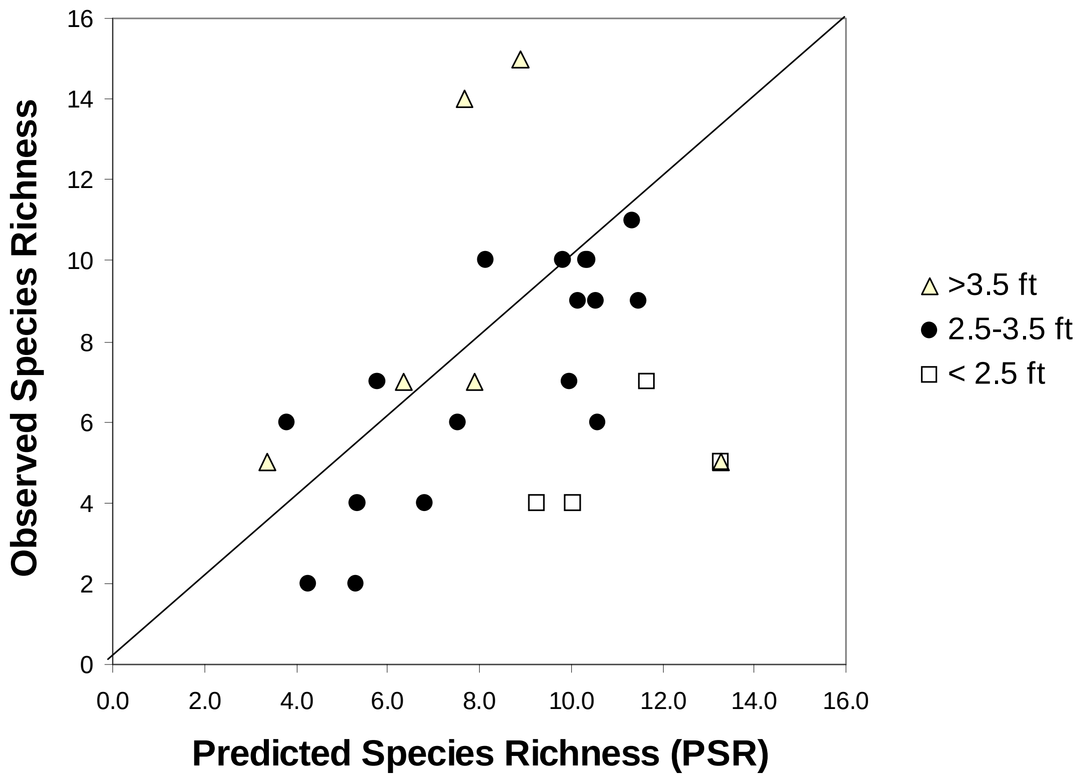

Figure 4-3. Relationship between predicted and observed species richness for tree islands in WCA 3A and 3B. Symbols show islands in three different categories based on maximum island elevation above the slough. The solid diagonal line indicates cases of a perfect fit between PSR and observed values.

PSR provides a joint hydrologic score that reflects areas of both flood and drought impacts using a single measure. This combined score avoids the interpretive complications that arise from using separate measures for drought and flood impacts that can allow a negative score on one measure to be offset by a positive score on the other. Local hydrology must be suitable at both ends of the hydrologic range in order for a grid cell to receive a high value of PSR.

A standardized value of PSR, denoted PSR*(c,x), is defined as the deviation of PSR in grid cell c of model x from the value predicted by NSM for the same grid cell, divided by the spatial standard deviation, σ_{NSM}, of PSR(c,NSM) calculated over all cells in a defined portion of the ridge and slough landscape:

$$PSR^*(c,x) = [PSR(c,x) - PSR(c,NSM)] / \sigma_{NSM}$$

Rescaling of PSR to standard deviation units creates a relative measure that avoids potential misinterpretation of PSR as a literal prediction of future species richness. It also creates a scale of measurement that allows differences in PSR to be related to the landscape pattern of variation in predicted species richness under simulated predrainage conditions. Standardization relative to NSM underscores that species richness is serving as an ecological response variable that identifies relevant variation in hydrology, and is not being set as the restoration goal for tree islands per se.

PSR*(c,x) can be defined for any single grid cell or group of grid cells c and any particular model x. For example, PSR*(c,x) could be defined for every grid cell in a water conservation area for a particular run of the SFWMM, and normalized using the NSM standard deviation for the same group of cells. Alternatively, NSM values for all cells in the historical ridge and slough landscape could be used to normalize PSR.

The last step in developing the habitat suitability index is to define the Species Richness Suitability Index (SRSI) that maps PSR* to the interval (0,1) as follows:

SRSI(c,x) = 1.0	if PSR*(c,x) $\geq$ 0.0
SRSI(c,x) =1.0 + PSR*(c,x)/2	if -2.0 < PSR*(c,x) < 0.0
SRSI(c,x) = 0.0	if PSR*(c,x) $\leq$ -2.0

This index is illustrated by the solid line in **Figure 4-4**. Here, a grid cell or group of cells receives the maximum score of SRSI = 1.0 if the predicted species richness meets or exceeds that predicted under NSM hydrology. If predicted species richness falls below the value predicted by NSM, SRSI decreases linearly to a minimum of zero when PSR(c,x) is two or more standard deviation units lower than the NSM value for the grid cell. Cells that score zero have predicted species richness values close to or below the low end of the range of values predicted by NSM for the reference set of ridge and slough grid cells.

An alternative SRSI is illustrated by the dashed line in **Figure 4-4**. In this case, only PSR values that deviate from NSM by more than one standard deviation unit receive less-than-perfect scores, and cells that predict too many species are penalized along with cells that predict too few. Results for this alternative SRSI are not included in this report.

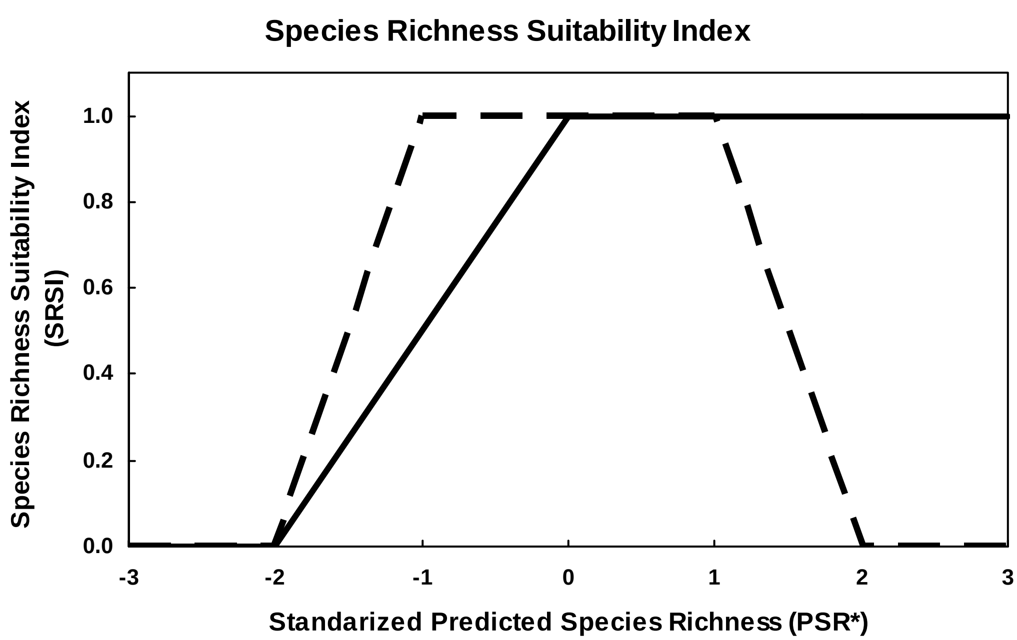

Figure 4-4. Species richness suitability indices (SRSI) for tree islands.

The SRSI is appropriate for evaluating model-to-model differences in the potential for adverse impacts to elevated tree islands over a multi-decade time scale. SRSI does not attempt to predict optimal depth conditions for tree island restoration, nor is it applicable as a performance measure for lower-elevation islands.

Tree Island Suitability Index

An alternative approach to developing habitat suitability indices is to construct a time series model that mimics the effects of flood stress and fire risk to tree islands over time. This approach uses information developed from landscape vegetation models that aim to provide realistic, dynamic models of vegetation change (Wu et al. 1996, 1997, 2002). Daily indices are developed to represent how flooding stress during high water periods and risk of fire during dry periods wax and wane as conditions vary. By providing a time series of values, this dynamic modeling approach may prove useful in identifying which specific hydrologic events or water management practices appear to be most likely to impact tree islands. A difficulty with the approach, however, is that the model parameters needed to characterize the rates at which stress and recovery occur are not presently known. These parameters must be inferred from field observations and reports in the literature, and they must be fitted during calibration of the model.

Flood Index

Based on Loveless' 1959 report that tree islands range from 1.0 to 3.0 feet in elevation relative to the surrounding marsh, along with more recent data on tree island elevations, a depth criterion of 2.0 feet was chosen for evaluating flooding stress to tree islands. Systematic studies of the relationship between the duration of tree island flooding and the time course of impacts to tree island species have not been conducted; hence, it is necessary to estimate the rate of deterioration of tree island condition from limited reports and field observations on the duration of flooding associated with noticeable stress at one extreme and widespread tree mortality at the other. Sixty days of continuous flooding above 2.0 feet was selected as an estimate of the point at which typical tree island species would begin to experience negative impacts, and 300 days of continuous flooding above 2.0 feet was selected as an estimate of the point at which extensive mortality would be expected. Given these assumptions, a daily flood index, DFI, is defined as the score for day t of the time series as follows:

$$DFI(t) = 1.0 / \{1.0 + 0.0023 \exp[0.039 \cdot CFD(t)]\}$$

where t = 1, . . . , 365N, for simulation of N years and CFD(t) is the cumulative flood duration in number of days of flood stress as of day t.

The shape of this DFI function is illustrated in **Figure 4-5**. The parameters of the above equation were chosen so as to set DFI(t) ~1.0 when CFD(t) = 60 days, and to allow continuous decrease in DFI(t) until DFI(t) ~ 0.0 when CFD(t) $\geq$ 300 days.

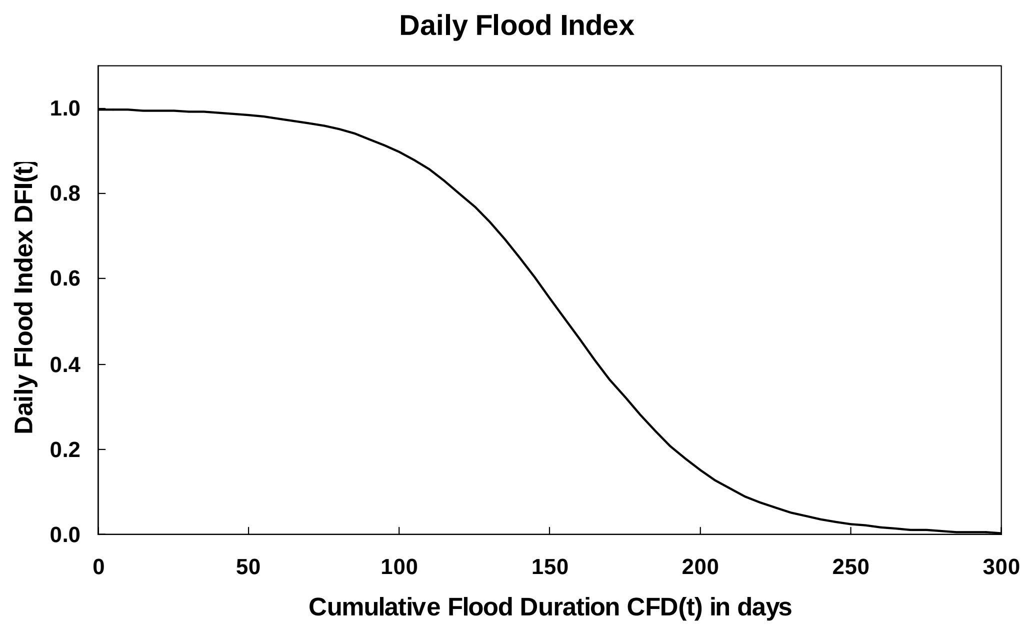

Figure 4-5. Daily flood index (DFI(t)) as a function of cumulative flood duration in days (CFD(t)).

The CFD(t) function defines the method for counting cumulative flood days as a function of water depths at time t, WD(t), as follows:

CFD(t) = CFD(t-1) + 1.0	if WD(t) > 2.0 feet
CFD(t) = CFD(t-1) - 0.5	if WD(t) is $\leq$ 2.0 feet and CFD (t-1) > 0.5
CFD(t) = 0	if WD(t) is $\leq$ 2.0 feet and CFD (t-1) $\leq$ 0.5

CFD(t) increases by the equivalent of one “flood day” for each additional day that water depth remains above 2.0 feet, and CFD(t) decreases by the equivalent of 0.5 “flood days” for each day depths have receded below 2.0 feet.

After examining several options (e.g., long-term mean and long-term minimum), the mean value over all years of the annual minimum of DFI(t) was selected as a summary measure of flood stress. This measure, the mean annual minimum flood index (MAMFI), provides an indication of the average maximum flood stress experienced by islands on an annual basis. For a time series of N years, MAMFI is defined as follows:

$$\text{MAMFI} = \sum_{i=1}^{N} \text{minDFI(i)/N}$$

where minDFI(i) is the minimum value taken by DFI(t) during year i.

Drought Index

The drought index proposed here is a dual-purpose tool. It can serve both as an index for assessing potential tree island impacts from drought, and as a stand-alone performance measure for evaluating the risk of peat-consuming wildfires in the overall ridge and slough landscape. Based upon review of historical records and the scientific literature, a depth of 1.0 feet below ground surface was selected as the best current estimate of the depth of ground water recession in peat marshes below which the risk of peat-consuming wildfires becomes excessive (SFWMD 2000).

The daily drought index, DDI(t), is defined as a time-dependent function of two variables: water depth, WD(t), and cumulative drought duration, CDD(t). CDD(t) is the number of sequential days up to and including day t during which depths were below ground surface, calculated as follows:

$$CDD(t) = 0 \qquad \text{if } WD(t) > 0.0 \text{ feet}$$

$$CDD(t) = CDD(t-1) + 1 \qquad \text{if } WD(t) < 0.0 \text{ feet}$$

The daily drought index is then defined as follows:

$$DDI(t) = 1.0 \qquad \text{if } WD(t) > 0.0 \text{ feet}$$

$$DDI(t) = \frac{1.0 - 0.0035CDD(t)}{1.0 + 0.010\exp\{-4.6WD(t)\}} \qquad \text{if } WD(t) < 0.0 \text{ feet}$$

Note that a single day with WD(t) > 0.0 feet is assumed to “break” the drought by resetting CDD(t) to zero and DDI(t) to unity. **Figure 4-6** illustrates the dependence of DDI(t) on the two variables. The numerator of DDI(t) decreases from a maximum of 1.0 when surface water is present to a minimum of zero when CDD(t) reaches 285 days. The coefficient 0.0035 is an approximate measure of the daily increase in the risk that a cell will be included in a wildfire (Wu et al. 1996). The denominator of the above equation serves to decrease the value DDI(t) as ground water recedes further below the surface. This feature of the index is intended to mimic the increased risk of intense and damaging muck fires when the soil has dried to greater depths.

The arithmetic average of the annual minimum of DDI(t) is proposed as a measure of long-term risk of fire, with increasing values of the index reflecting a decrease in the average annual risk. This mean annual minimum drought index (MAMDI), is defined for a series of N years as follows:

$$MAMDI = \sum_{i=1}^{N} minDDI(i)/N$$

where minDDI(i) is the minimum value taken by DDI(t) during year i.

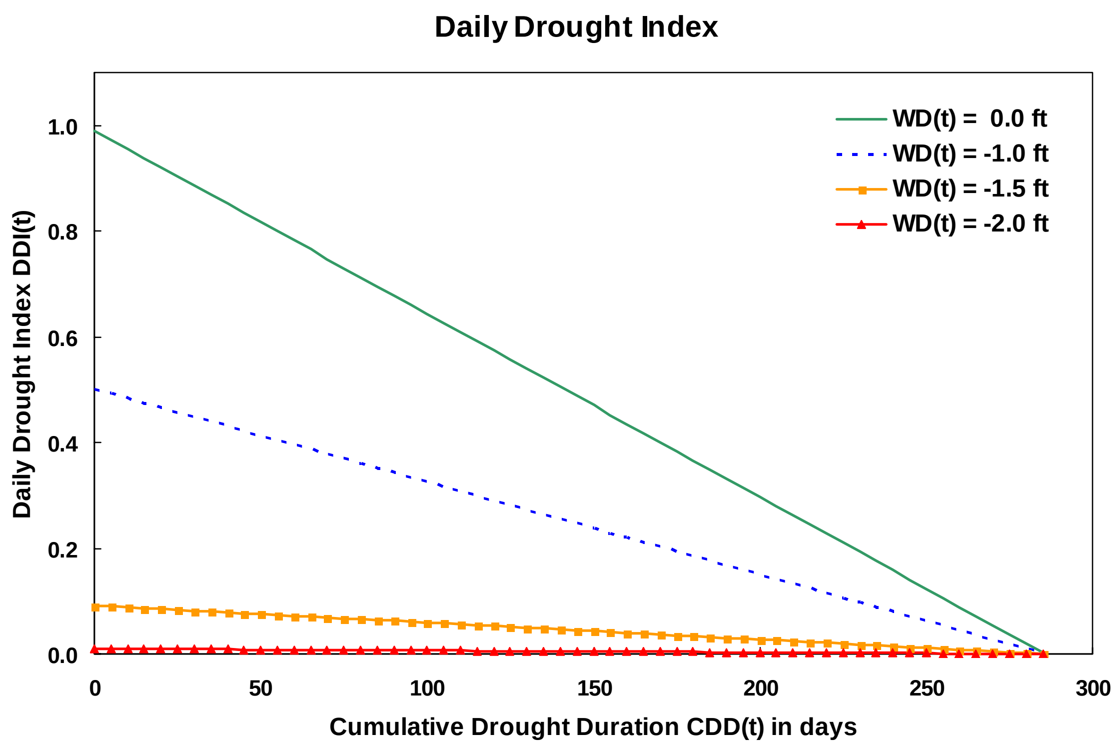

Figure 4-6. Daily drought index DDI(t) as function of cumulative drought duration in days CDD(t) and water depth below the surface WD(t).

Tree Island Suitability Index

In order to evaluate the combined effects of flood and drought on tree islands, the overall tree island suitability index (TISI) is defined as follows:

$$\mathrm{TISI} = \sum_{i=1}^{N} \mathrm{minDDI(i)} \cdot \mathrm{minDFI(i)/N}$$

This equation assigns, for each year, a value that is at most as large as the smaller of the two indices during that year. TISI is then the long-term mean of these values. This formulation insures that high scores for one index during a given year cannot mitigate the impact of a low score for the other index. This prevents flood and drought year values from canceling each other out. It also compounds the effect of flooding and drought in any year by making the overall TISI value less than each of the individual flood or drought indices.

An alternative formulation of TISI is to use the annual minimum of the MAMFI and MAMDI. This assigns a value for each year that is equal to the smallest value taken by either index during the year. An alternative tree island suitability index, not discussed further in this report, could be defined as follows:

$$\mathrm{TISI_{alt}} = \sum_{i=1}^{N} \mathrm{min[DDI(i), DFI(i)]/N}$$

Results

The suitability indices developed above have not been subject to rigorous evaluation and cross-validation. However, the following sections present some initial results and observations relevant to the performance of these indices as plan evaluation tools for the simulated natural, current, and restored systems.

Species Richness Suitability Index

PSR scores for the natural system (**Figure 4-7a**) are relatively high throughout the ridge and slough landscape. Since the derivation of PSR was based on empirical data that are independent of NSM results, this lends support to the notion that restoration of natural hydrology would be expected to contribute to the restoration of tree island vegetation communities. Under current system hydrology, PSR scores (**Figure 4-7b**) are relatively low in areas where there has been a shift away from natural system hydrology through excess drying in northern WCA 3 and the Rotenberger Wildlife Management Area or excess high water to the northwest of the L-67 canal and in southern Arthur R. Marshall Loxahatchee National Wildlife Refuge (LNWR) and WCA 2B. For the hydrology of the restored system, PSR scores (**Figure 4-7c**) improve relative to the current system for most of northern WCA 3, for the Rotenberger Wildlife Management Area, and along the L-67 canal. These observations lend mutual support for both PSR as a performance measure and the natural system as simulated using the NSM model as a suitable planning target. However, PSR by itself is not a suitable metric for evaluating tree island condition, because maximization of species richness per se is not a restoration goal. Rather, it is expected that hydrologic restoration would support the recovery of tree islands to levels of biodiversity that are comparable to those that existed prior to drainage of the Everglades. Hence, evaluation of hydrologic models is based on SRSI, which measures the deviation of PSR from a target based on simulated natural system hydrology.

The spatial distribution of SRSI (calculated using the solid line in **Figure 4-4**) for the current and restored systems (**Figure 4-8**) suggests that the restoration plan would improve tree island condition through most of WCA 3A, WCA 3B, and Shark River Slough. Slight improvements are predicted for the Arthur R. Marshall Loxahatchee National Wildlife Refuge (LNWR). In WCA 2A, SRSI predicts improvement in the northern part of the water conservation area but negative impacts in the central and southern regions.

Tree Island Suitability Index

Components of the TISI are the annual minimum flood and the annual minimum drought indices. Examination of the mean values of these two indices provides information on their individual performance.

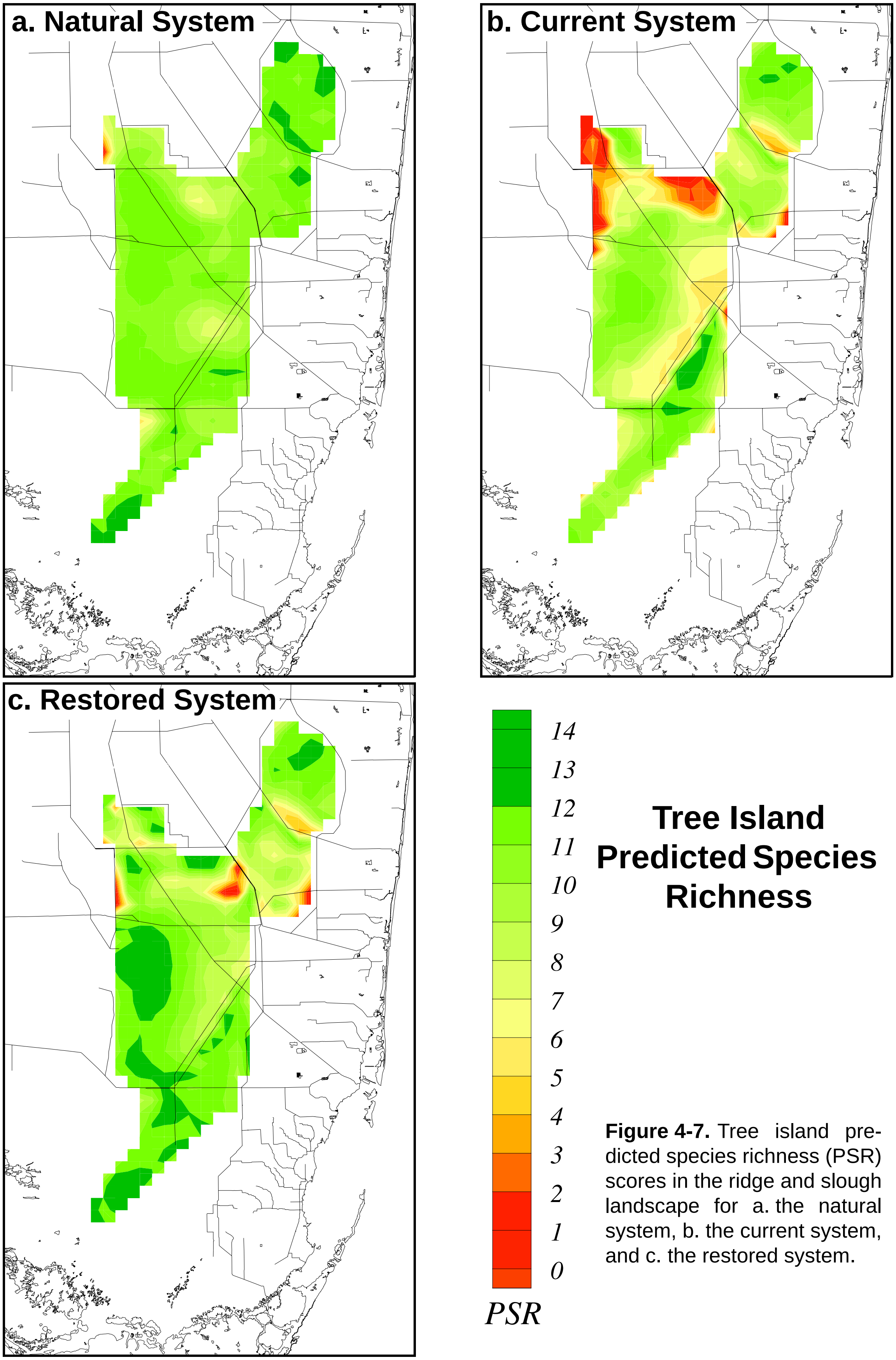

Figure 4-7. Tree island predicted species richness (PSR) scores in the ridge and slough landscape for a. the natural system, b. the current system, and c. the restored system.

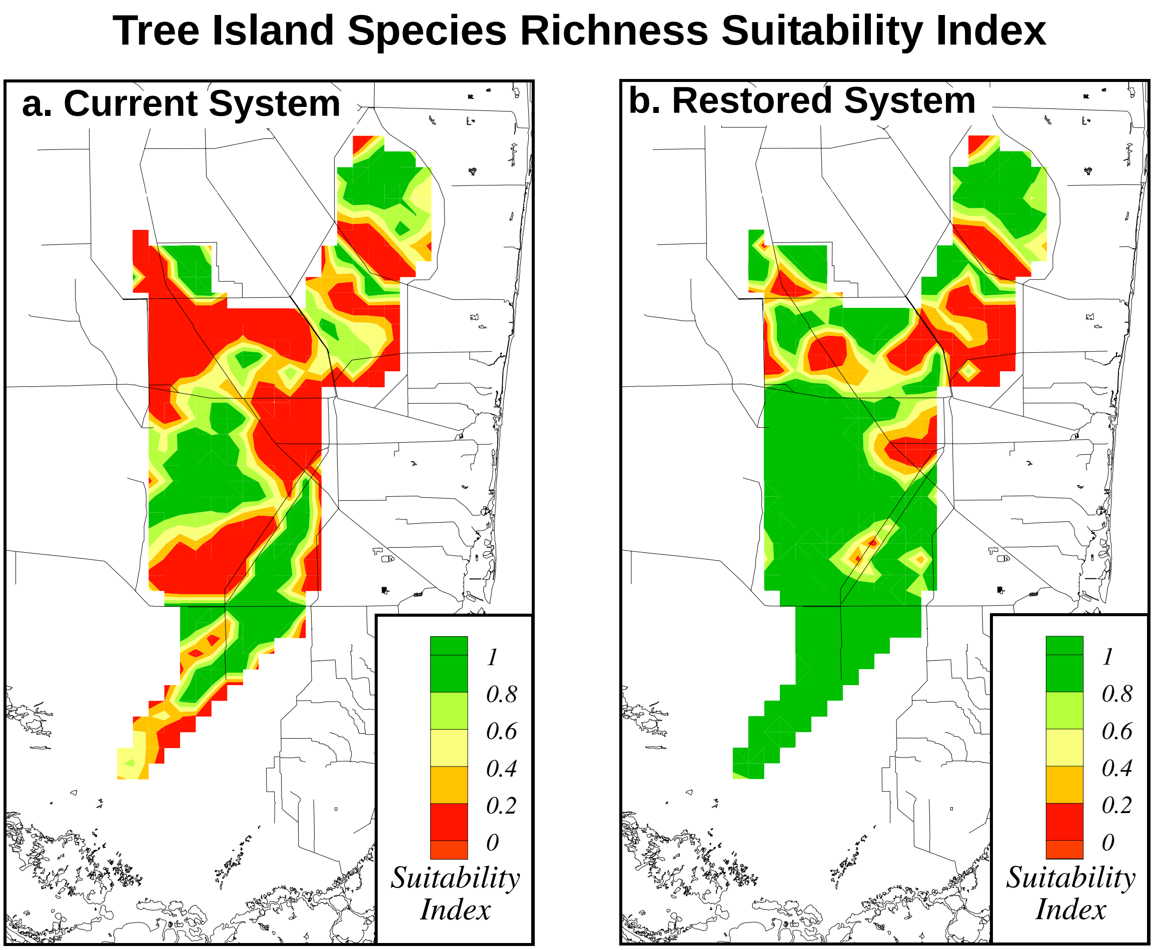

Figure 4-8. Tree island species richness suitability index (SRSI) in the ridge and slough landscape for the a. current system and b. restored system. By definition, SRSI = 1.0 for all cells for the NSM.

Flood Index

The spatial distribution of MAMFI for the natural, current, and restored systems is illustrated in **Figure 4-9**. For the current system, the MAMFI correctly identifies the regions where tree island flooding has been common during recent decades, namely southern LNWR and southern and eastern WCA 3A (**Figure 4-9b**). In the restored system, improvements are predicted in southern WCA 3A, but increased tree island flooding is predicted for WCA 3B, northeast Shark River Slough and southern WCA 2A (**Figure 4-9c**). A possible anomaly appears in the MAMFI values for the natural system (**Figure 4-9a**), which shows the expected high scores everywhere except northeast Shark River Slough, where index values are low. This could be an indication of a need to better calibrate the flood index to accommodate deeper regions of the ridge and slough landscape. Alternatively, the low scores could be artifacts of the NSM model topography for northeast Shark River Slough, which has not been adjusted for soil subsidence that is believed to have occurred in this area (Stober et al. 1998).

Drought Index

The spatial distribution of the MAMDI for the natural, current, and restored systems is illustrated in **Figure 4-10**. The natural system receives relatively high scores throughout the ridge and slough landscape (**Figure 4-10a**). In the current system, the index correctly identifies areas of northern WCA 3A, northern LNWR and northeastern WCA 2B that have been subject to significant impacts from drought (**Figure 4-10b**). The restored system shows improvement over the current system; however, relatively low index values are still observed in parts of northern WCA 3A and northern LNWR, and index values in central and southeastern WCA 2A and in eastern WCA 2B are slightly lower than those for the current system (**Figure 4-10c**).

Tree Island Suitability Index

The spatial distribution of the composite TISI for the natural, current, and restored systems is illustrated in **Figure 4-11**. Results for the natural system indicate generally favorable conditions for tree islands throughout the ridge and slough landscape, with the exception of northeast Shark River Slough, again associated with low values for the flood index (**Figure 4-11a**). The index correctly identifies the most heavily impacted areas in WCA 3A in the current system (**Figure 4-11b**). The failure to identify observed impacts to tree islands in WCA 2A is probably a result of the operational assumptions used in modeling the current system. Water levels were simulated using the existing regulation schedule for WCA 2A, which differs from and is more favorable than past operations that resulted in impacts to tree islands in this area (Dineen 1972, 1974). The index values for the restored system suggest that tree island conditions will improve considerably in WCA 3A and Shark River Slough, with slight improvements in northern WCA 2A (**Figure 4-11c**). However, conditions in southern WCA 2A and WCA 3B are predicted to decline slightly in the simulated restored system.

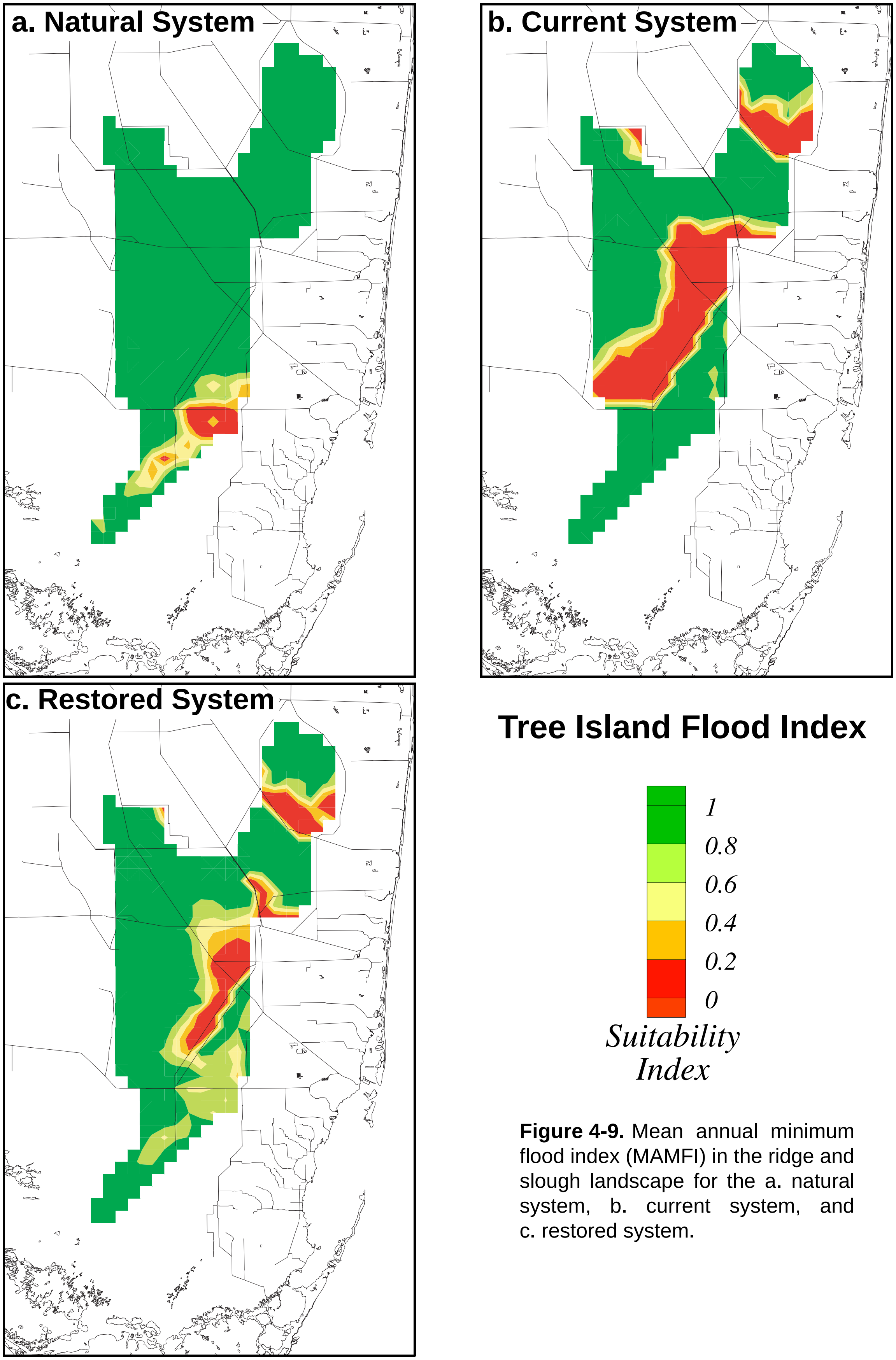

Figure 4-9. Mean annual minimum flood index (MAMFI) in the ridge and slough landscape for the a. natural system, b. current system, and c. restored system.

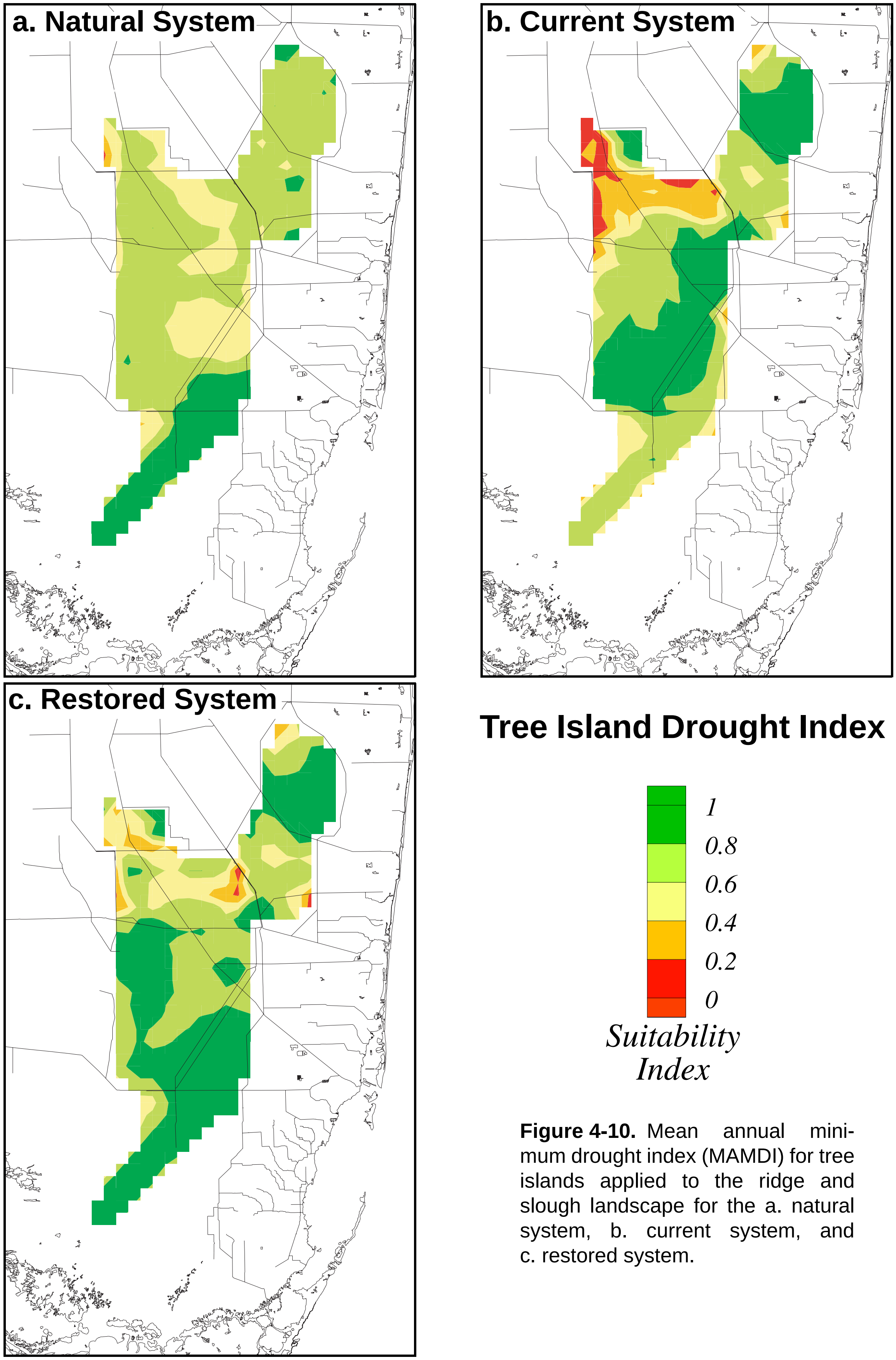

Figure 4-10. Mean annual minimum drought index (MAMDI) for tree islands applied to the ridge and slough landscape for the a. natural system, b. current system, and c. restored system.

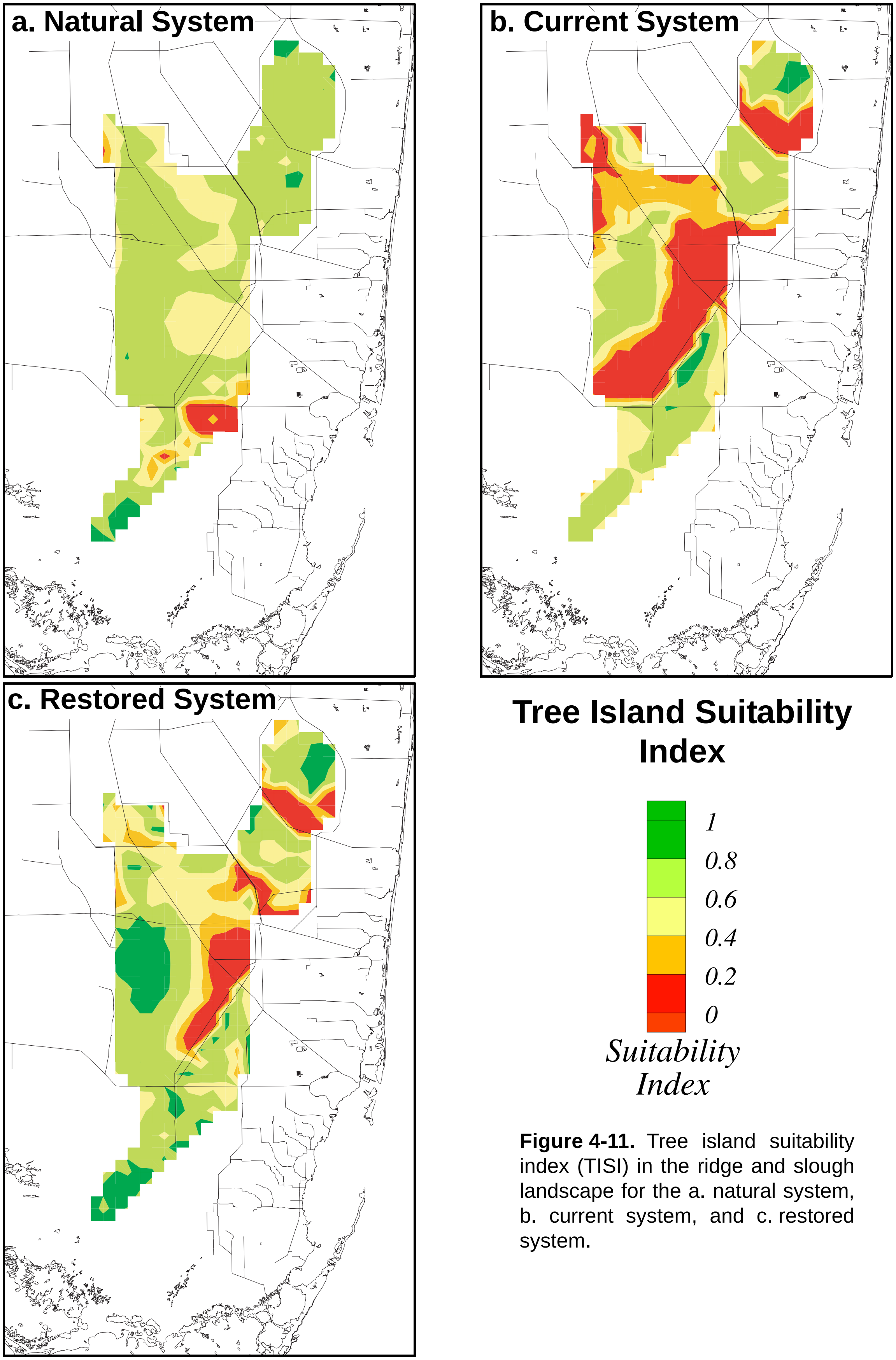

Figure 4-11. Tree island suitability index (TISI) in the ridge and slough landscape for the a. natural system, b. current system, and c. restored system.

Discussion

Figures 4-8 and **4-11** show the spatial distribution of the two indices, SRSI and TISI, across the ridge and slough landscape. For both the current and restored systems, the two indices exhibit similar overall landscape patterns. However, two broad differences are apparent.

First, SRSI exhibits more low (< 0.2) and high (> 0.8) scores (red and green) and fewer intermediate scores than does TISI; it is therefore a more "decisive" index. For the current system, of the 437 model cells representing the ridge and slough landscape, SRSI assigned intermediate (0.0 < SRSI < 1.0) values to 198 cells (45 percent of the area), whereas TISI assigned intermediate values to 399 cells (91 percent of the area). Given this, TISI may be more useful than SRSI in making comparisons among similar model scenarios that have small differences in index scores. However, if index values are uncertain, small differences may be uninformative, and a "blunt" tool such as SRSI may be preferable.

Second, TISI assigns lower scores to areas that have been subject to tree island flooding, and higher scores to areas subject to frequent drought, when compared to SRSI. An explanation for this can be found in the ranges of values of the component indices that contribute to TISI. The flood index MAMFI (**Figure 4-9**) exhibits a larger range of values than does the drought index MAMDI (**Figure 4-10**), having more scores in the "red" zone and fewer intermediate values. Because TISI is based on the product of the annual minima of the two indices, TISI produces lower values in flooded areas than in dry areas. The values of the flood and drought indices are not standardized relative to each other; hence, the difference in their contribution to the final TISI score may not be ecologically meaningful. Using $TISI_{alt}$, the alternative index based on the annual minimum of either MAMFI or MAMDI, does not overcome this inadvertent emphasis on the flood index.

The weighting of the flood and drought scores in SRSI is derived from a multiple regression analysis of species richness on drought and flood measures, and thus these weights employ the statistically observed contribution of the two hydrologic variables as predictors of species richness. This may in principle provide a more ecologically meaningful weighting system. However, it is important to note that the tree island data used to develop SRSI come from an area in which drought impacts have accumulated over a much longer period of time than have impacts from island flooding. Loveless (1959) reported significant fire damage to tree islands in northern WCA 3A by the 1950s. This was well before the impoundment of WCA 3A in the mid-1960s that introduced excess flooding as a significant factor affecting tree islands. It is therefore quite possible that SRSI may implicitly weigh drought impacts disproportionately relative to flood impacts, simply because they have accumulated over a longer period of time. Given these interpretive issues, it can be seen that neither index is expected to correctly predict the *relative* importance of flood versus drought as tree island stressors. Rather, the indices should only be used to make model-to-model comparisons between matched regions of the model domain and should not be used to compare impacts in flooded regions to those in drained ones.

An important issue to be addressed regarding use of the habitat suitability indices is the degree to which the indices can be generalized for application to all parts of the ridge and slough landscape. Both SRSI and TISI were based on data and expertise associated with particular subregions. SRSI was derived using data from tree islands in WCA 3A (Heisler et al. 2002); TISI was based on field data and landscape modeling in WCA 2A (Wu et al. 1996, 1997) and WCA 3A (Wu et al. 2002). Whether or not they are broadly applicable across the entire ridge and slough landscape remains to be assessed.

Drought impacts to tree islands are mediated by common causal mechanisms of microbial oxidation and fire; thus, one would expect that an index suitable for one region of the peat-forming Everglades should apply to all such regions. It is possible, however, that if regions differ in soil thickness, the drought index may provide scores that are not comparable between regions by assigning similar values to areas that differ in vulnerability to fire. This reinforces the need to avoid cross-region comparisons.

Flooding effects are less likely than are drought effects to share common evaluation criteria across the ridge and slough landscape. Generalization of the flood index across regions requires a consideration of regional variation in tree island height and composition. For example, LNWR is a unique area having numerous and distinctive “pop-up” tree islands, which may respond differently to high water conditions than the large fixed tree islands in WCA 3 and Shark River Slough. Likewise, Shark River Slough is a region where historic depths probably exceeded those in the ridge and slough landscape to the north. In a restored ecosystem, similar tree island vegetation communities in Shark River Slough might occur at higher relative elevations than they would on islands in the water conservation areas.

Given our limited present knowledge of tree island elevations and the nature of flooding effects, SRSI may be more safely generalized to areas outside of WCA 2 and WCA 3 than TISI. SRSI is based on two variables, frequencies of depths above 2.0 feet and below -1.0 foot, that can serve broadly as indicators of extreme depth conditions so long as they are scaled appropriately for each region. Because SRSI uses the local natural system (NSM) hydrology to define its target, scaling to different NSM hydropatterns is built directly into the index. In contrast, TISI employs absolute benchmarks for acceptable depths and durations of high and low water. Thus, TISI is more likely to require calibration in order to be applied in different regions. A drawback to the use of SRSI, is that it assumes that the NSM provides an accurate representation of historical hydropatterns as well as a good approximation of the depth conditions that would support tree islands in the current, modified Everglades landscape. The utility of SRSI is thus tied to the validity of NSM hydrology as a restoration target. Given these caveats, the use of SRSI to evaluate tree island impacts in LNWR and Shark River Slough may be reasonable.

Application of either TISI or SRSI in the remnant sawgrass plains of northeastern WCA 3A and the Holey Land Wildlife Management Area is not warranted, owing to the absence of tree islands in these areas. However, the use of the drought index MAMDI seems both appropriate and valuable in these regions, owing to their histories of overdrainage and peat fire. The Rotenberger Wildlife Management Area contains tree

islands that have lost elevation owing to past wildfires. In this area (and possibly others yet to be identified), the use of natural system hydrology to define appropriate high water values may be inappropriate, and SRSI may not be applicable without modification of its "target" value.

In summary, SRSI is probably more likely to be broadly applicable across the ridge and slough landscape, because it is unambiguously tied to empirical data, is simpler in structure, and is scaled to match spatial variation in hydropatterns estimated by NSM. TISI shows promise as a method for providing a representation of stress and recovery of islands as a function of hydrologic change over time. At present, application of TISI may best be restricted to WCA 2A and WCA 3A, pending additional cross-validation and calibration. Overall, the most robust evaluations may be achieved by applying both indices simultaneously. This approach would enable planners to explicitly consider the strengths and limitations of both indices, and to use differences between index results to identify areas where the response of tree islands to proposed hydrologic change is least certain.

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CHAPTER 5

Periphyton Habitat Suitability Index

Evelyn E. Gaiser[1], Dan L. Childers[1], Joan A. Browder[2], Steve M. Davis[3], and Kenneth C. Tarboton[3]

General Description

Periphyton (**Figure 5-1**) is a ubiquitous feature of Everglades marshes and has been shown to respond strongly in structure and function to alterations in both hydrologic conditions and water quality. Through interactions with the physiochemical environment and other biota, periphyton influences many features of the Everglades ecosystem including soil quality, secondary production, concentration of nutrients, and dissolved gasses. Therefore, it is not only a sensitive indicator of environmental change but can serve as an early warning signal of impending change in other components of the ecosystem.

Figure 5-1. Floating periphyton mats.

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2. National Oceanic and Atmospheric Administration
3. South Florida Water Management District

Studies of variation in Everglades periphyton along naturally existing and experimentally created gradients have found strong relationships of species composition, nutrient content and ratios, structure (growth form), calcite content, and physiology (i.e., nutrient uptake, productivity) to water quality and quantity (Browder et al. 1982, Swift and Nicholas 1987, Grimshaw et al. 1993, Raschke 1993, Vymazal and Richardson 1995, McCormick et al. 1996, McCormick and O'Dell 1996, McCormick et al. 1997, Cooper et al. 1999, Pan et al. 2000, McCormick et al. 1998). The type and sensitivity of response depends on the type and influence of the manipulated variable. Hydroperiod and nutrient alterations have different effects on different systems. Nutrient enhancement in an oligotrophic system would elicit a different suite of responses from that in a nearby degraded system. The quantity of supporting data and the spatial extent of applicability of those data is variable. Currently, much more data exist on effects of accelerated phosphorus loading on periphyton than effects of alterations in hydropattern and most studies have been confined to a few specific areas.

Few studies have evaluated the interaction of these two variables on periphyton. Although some useful generalizations may be obtained by integrating results from phosphorus-dosing experiments conducted in marshes of differing hydroperiod. For these reasons, we based the suitability indices on relationships that have the most empirical support and we explicitly state the certainty and range of applicability of resulting models. The formulation of these models has resulted in a list of research needs, included at the end of this chapter, with the expectation that the suitability indices will evolve over time with the generation of novel results.

Hydrologic Variables

The periphyton-based hydrologic suitability index was partitioned into three separate models because three structurally different communities occur across the Everglades hydroscape (Browder et al. 1994). Structural and functional responses to hydroperiod alterations vary depending on the hydroperiod range to which the mat has been historically exposed. Periphyton in short-hydroperiod marshes (flooded 0-8 months) is typically consolidated into either sediment-associated mats or "sweaters", the thick, spongy coatings on submerged stems of emergent macrophytes. Because they are associated with a limestone substrate and are regularly exposed to oxidation, these mats are typically highly calcareous. Persistent flooding in longer-hydroperiod marshes (flooded 8-30 months) encourages production of submerged macrophytes that become an important floating substrate for periphyton. Floating calcareous mats, often termed "metaphyton", predominate in these systems. Finally, the longer-hydroperiod marshes (flooded more than 30 months) of the Arthur R. Marshall Loxahatchee National Wildlife Refuge (LNWR) contain a peat-forming plant community that supports a very different, acid-loving epiphytic periphyton assemblage.

The parameters used to measure suitability of a particular hydroperiod range differ according to the community type, but will be a designated subset of the following features: proportion of mat existing in the optimal growth form for the hydroperiod range, aerial cover of the mat, proportion of nonblue-green algae, proportion organic content and

presence of preferred attachment substrate. The form of the final suitability function for each hydroperiod range is a composite of the responses of the selected parameters and the three models can be mathematically combined into a composite function that encompasses the entire gradient. All three models are solely a function of the period-of-simulation (31 years) average hydroperiod computed from South Florida Water Management Model version 3.5 (SFWMM) and Natural System Model version 4.5 (NSM) output. The SFWMM and NSM grid cells applicable to these periphyton communities for the periphyton suitability index are presented in **Figure 5-2**.

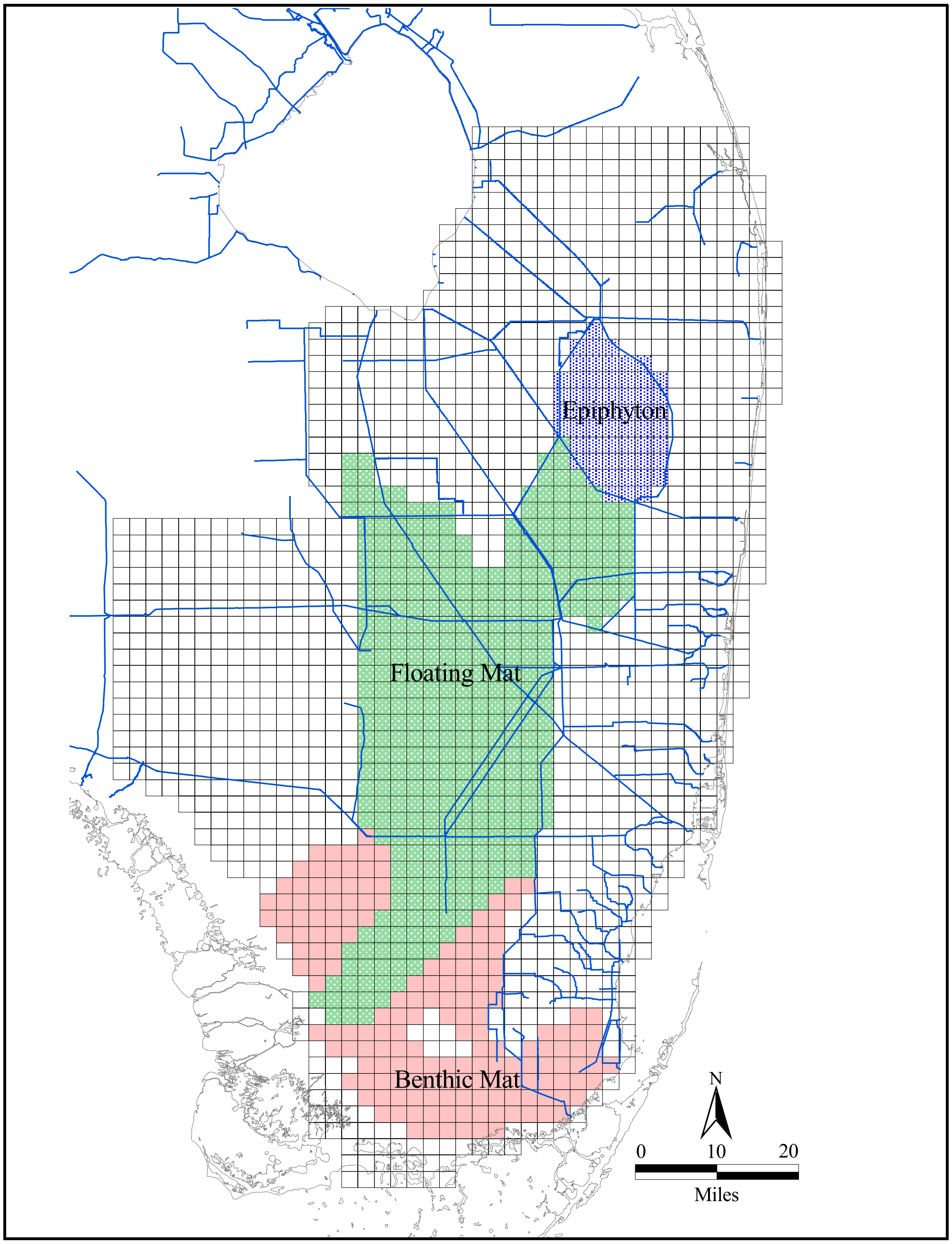


Figure 5-2. SFWMM grid cells applicable to the three different periphyton communities of the periphyton habitat suitability index.

Habitat Suitability Functions

Benthic Periphyton

Benthic, or sediment-associated, periphyton mats are an important component of shallow, short-hydroperiod Everglades marshes (Browder et al. 1994). Floating macrophytes are typically absent from these marshes so metaphytic periphyton mats are rare. However, often associated with benthic mats in these systems are thick growths of epiphytes, or sweaters, on the submerged stems of the emergent macrophytes (typically either *Eleocharis* spp. or *Cladium jamaicense*). For the purposes of our models, we combine benthic and sweater-forming mats into a single category. Benthic mat models should be applicable to areas with an average hydroperiod of less than 8 months, which includes eastern Shark River Slough, Taylor Slough (see **Figure 3-1**), northwestern Shark River Slough and portions of Water Conservation Area (WCA) 3A (to the north) and WCA 2A (central) (see **Figure 1-1** for location of all areas except Taylor Slough). Three features contribute to the suitability index for benthic mats: 1) percent benthic/sweater periphyton of total periphyton biomass, 2) percent organic content of mat, and 3) proportion of the community comprised of nonblue-green algae.

Percent Benthic Periphyton

Benthic periphyton mats are usually absent from marshes that are only flooded for a few days. However, because mats are dominated by species that are relatively resistant to desiccation, they regenerate fairly quickly after prolonged drying. Thin periphyton films appear on lime rock or marl substrate after days of reflooding while thick mats may take several years of repeated 1 to 2 month flooding episodes to form. Once formed, these mats form a fairly uniform cover across large areas and only disappear when 1) water depths increase above 2 feet when carbonate dynamics and light attenuation limit production and 2) hydroperiod exceeds the point that limits the production of metaphyton-supporting submerged plants (i.e., *Utricularia purpurea*, which becomes important when hydroperiods exceed 8 months).

Percent Organic Content of Mat

Because benthic mats proliferate in short-hydroperiod marshes, they are frequently exposed to oxidative removal of accumulated organics. They form on lime rock substrates and are calcitic, contributing to the marl soils that characterize these marshes. The percent organic material in benthic mats increases with increasing hydroperiod.

Percent Nonblue-green Algae in Mat

Most mat taxa are relatively resistant to periodic desiccation but some return more quickly than others after reflooding events. The mat-forming filamentous blue-green algae have been shown to be particularly drought-resistant. Although diatoms and green algae are generally not as resistant to drought, some species have been identified as “aerophilic” and capable of withstanding prolonged drought. Work in the Everglades to define these

taxa is under way but data are not yet ready for incorporation into these models. Data from limited surveys and ongoing experimental work suggest that the best community-based index of hydroperiod for benthic mats will come from the ratio of filamentous blue-green algae to other elements in the mat. This ratio increases with the duration of drought (Browder et al. 1981, E. Gaiser, Florida International University, unpublished data, A. Gottlieb, Florida International University, unpublished data). Because this ratio shows strong promise in providing early indication of ecological effects of altered hydroperiod, it should be considered a major research need.

Benthic Periphyton Suitability Index

Based on these three features, a benthic periphyton suitability index (BPSI) as a function of the average hydroperiod over the period of simulation (t in months) is defined as follows (**Figure 5-3**):

$$BPSI = 1 - \exp[-(t/2)^3] \text{ for } t \leq 4 \text{ months}$$

$$BPSI = \exp[-(t/14)^7] \text{ for } t \geq 4 \text{ months}$$

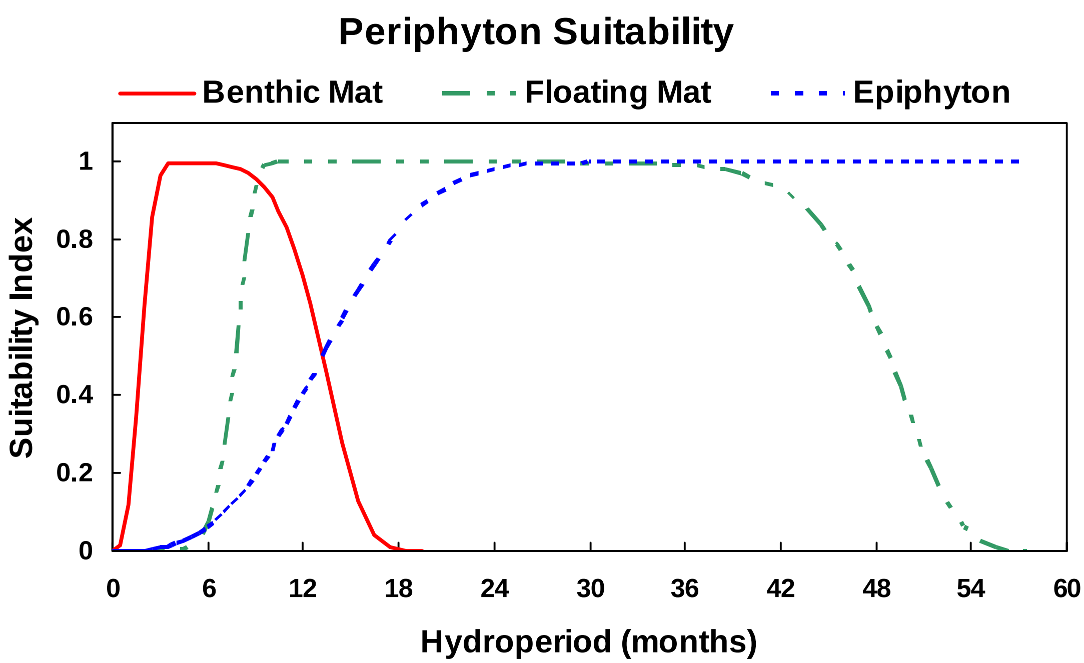


Figure 5-3. Periphyton suitability as a function of hydroperiod for benthic, floating and epiphytic mat communities.

Floating Periphyton

In deeper, longer-hydroperiod Everglades marshes, periphyton occurs either in benthic aggregations, sweaters on submerged stems of emergent macrophytes, or as floating metaphyton on submerged macrophytes. The latter is the predominant form of periphyton in central Shark River Slough and WCA 3A. The formation of floating mats

appears dependent on the availability of floating substrate, most often the purple bladderwort, *U. purpurea*, which is poorly adapted to desiccation and, therefore, excluded from shorter-hydroperiod sites. Thick floating periphyton mats substantially reduce light penetration to sediments and, therefore, prohibit the coexistence of productive benthic periphyton mats. The upper hydroperiod limit for floating mats appears to be determined by carbonate dynamics. Floating mats do not occur in acidic wetlands with peat soils that have formed during episodes of prolonged flooding (i.e., LNWR). Floating mats are presently the predominant form of periphyton in ridge and slough wetlands with hydroperiods ranging from 8 to 30 months, which includes central Shark River Slough, and most of WCA 3A and WCA 2A. Three features contribute to the suitability index for floating mats: 1) percent aerial cover of floating mat, 2) percent organic matter content of mat, and 3) abundance of the preferred attachment substrate, *U. purpurea*.

Percent Aerial Cover of Floating Mat

Floating mats typically occur in patches associated with *U. purpurea* in *Eleocharis*, sparse *Cladium*, and *Nymphaea*-dominated marshes. Patchiness is on the order of several meters and appears correlated with the patchiness of the vegetation. Areas that are for various reasons devoid, but surrounded by, floating mats typically have benthic or sweater periphyton communities. This patchiness must be taken into account in evaluating periphyton cover. In addition, floating periphyton mats undergo a seasonal senescence, possibly related to the seasonality of *U. purpurea*. Therefore, we can define two models that relate floating periphyton mat cover to hydroperiod: one for the dry season and one for the wet season. These can be expressed as one function of hydroperiod, but mat cover varies.

Percent Organic Content of Mat

The organic content of floating periphyton mats is correlated with hydroperiod and water depth. Periphyton in shallow, short-hydroperiod wetlands typically have greater access to bicarbonate, which is removed by filamentous blue-green algae and precipitated into calcite crystals that maintain the structural integrity of the mat. In peat-based, longer-hydroperiod wetlands, the pH is typically lower and periphyton is predominantly comprised of highly organic, noncalcareous algae that do not form floating conglomerates. Data showing the relationship of periphyton organic content to hydroperiod helps us define the suitability index as a function of hydroperiod.

Abundance of U. purpurea

Floating periphyton mats are often associated with the submerged macrophyte *U. purpurea* that forms the backbone of the mat. While other species of bladderwort are common in shorter-hydroperiod marshes, *U. purpurea* is usually absent from marshes that are flooded for less than 4 months. Rather, it is an important component of the ridge and slough system, and shares a common distribution with *Nymphaea odorata* and other slough macrophytes. *U. purpurea* is abundant in acidic portions of the system (i.e., LNWR) as well, but in these areas it does not support a calcareous floating mat but rather is coated by a thick organic-rich epiphytic periphyton community.

Floating Periphyton Suitability Index

Based on these three features, a floating periphyton suitability index (FPSI) as a function of the average hydroperiod over the period of simulation (t in months) is defined as follows (**Figure 5-3**):

$$FPSI = 1 - \exp[-(t/8)^9] \text{ for } t \leq 10.5 \text{ months}$$

$$FPSI = \exp[-(t/50)^{15}] \text{ for } t \geq 10.5 \text{ months}$$

Epiphytic Periphyton

In peat-based wetlands with deeper water and longer hydroperiods, periphyton is abundant but does not form calcareous conglomerated mats (Gleason and Spackman 1974, Swift and Nicholas 1987). Rather, the periphyton is a flocculent algae and bacteria-rich matrix that grows attached to the submerged stems of aquatic plants. This is the predominant form of periphyton in LNWR. This type of epiphytic periphyton should not be confused with “sweaters”, which are calcareous aggregations that form in short-hydroperiod wetlands. Three features contribute to the suitability index for epiphytic periphyton: 1) percent organic matter content, 2) percent nonblue-green algae in the periphyton, and 3) abundance of submerged attachment surfaces.

Percent Organic Matter Content

The organic matter content of periphyton is highly correlated with hydroperiod, particularly at the upper end of the hydroperiod spectrum. Epiphytic periphyton aggregations, occurring in the longest hydroperiod marshes, are nearly 100 percent organic being incapable at the resident pH of precipitating calcite crystals. A decrease in hydroperiod in LNWR, however, may not induce the production of calcitic floating mats as would be predicted with the hydroperiod model alone. Because LNWR is situated on a silica-sand substrate rather than lime rock, the pH may remain low enough to prohibit the formation of a calcite-precipitating periphyton flora.

Percent Nonblue-green Algae

Recent studies across the Everglades system suggest that as hydroperiod and water depth increase, the abundance of filamentous blue-green algae that thrive in shallow, calcareous wetlands decreases. Communities in LNWR are dominated by an entirely different assemblage of acid-loving taxa, including an abundance of desmid algae and diatoms (Gleason and Spackman 1974, Swift and Nicholas 1987). This flora may have been important in large areas of the northern Everglades before modern canal construction increased the pH and decreased the water levels in adjacent marshes (Slate and Stevenson 2000). It would be expected to reappear in these areas if hydroperiod was lengthened, but the return may happen slowly, only after peat accumulations deepen and pH is reduced below approximately 6 to 7. As for benthic mats, a model that directly explains the relationship between nonblue-green algae and hydroperiod and/or water depth should be a

major research aim because of the potential applicability in providing a reliable index of changing water availability.

Abundance of Attachment Substrate

In acidic wetlands with an abundance of submerged macrophytes, epiphytic periphyton predominates. It may be excluded when vegetation becomes too dense to permit light penetration to stems but also when water depth exceeds the limits that support the growth of macrophytes. At this upper end, epiphytic algal assemblages are replaced by phytoplankton. This depends on limits to the depth of growth of macrophytes that exceeds depths currently represented in the Everglades system.

Ephiphytic Periphyton Suitability Index

Based on these three features, an epiphytic periphyton suitability index (EPSI) as a function of the average hydroperiod over the period of simulation (t in months) is defined as follows (**Figure 5-3**):

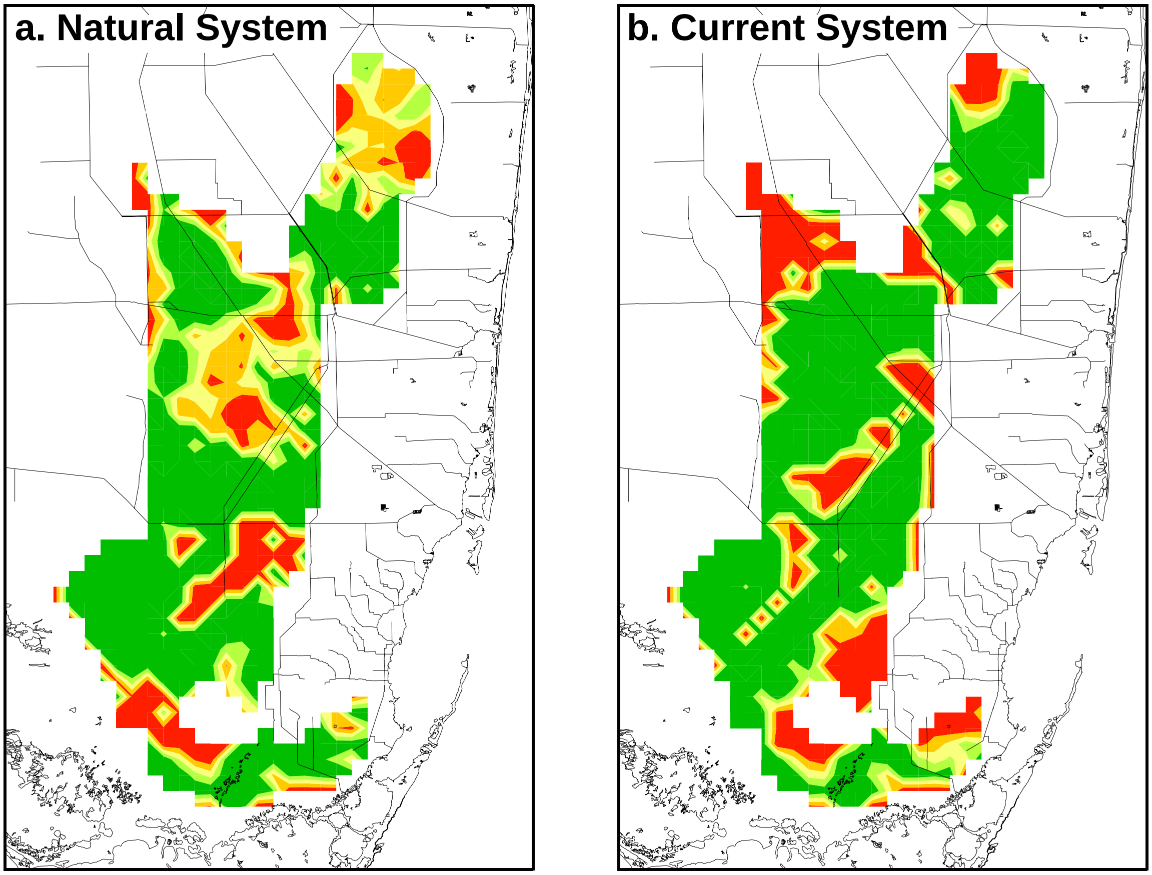
$$\text{EPSI} = 1 - \exp[-(t/15)^3]$$

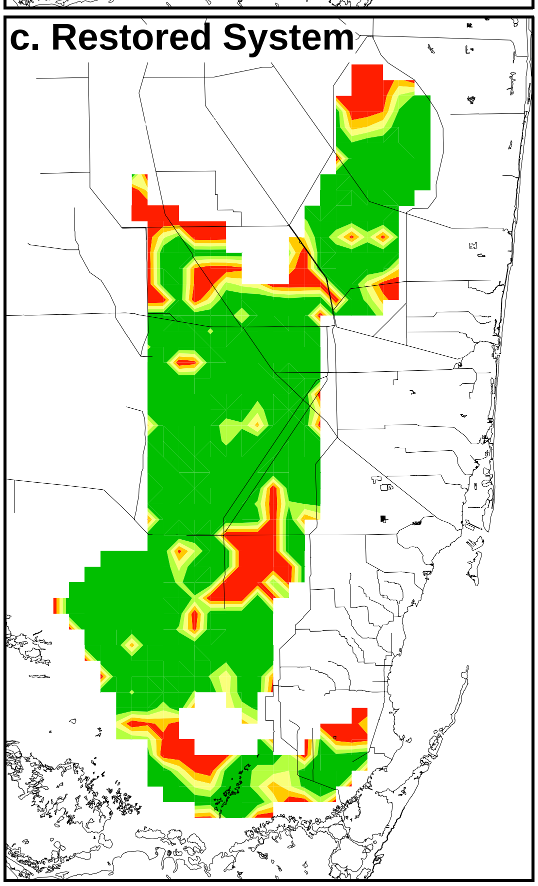
Results

Initial results indicating the performance of the periphyton suitability indices are shown for the natural, current, and restored systems in **Figure 5-4**. Periphyton suitability is a direct function of the average hydroperiod for the period of record (31 years from 1965-1995) as indicated in **Figure 5-5**.

The epiphyton habitat suitability index was applied to LNWR (**Figure 5-2**). Simulated natural system hydroperiods were typically 8 to 12 months with some areas experiencing hydroperiods longer than a year (**Figure 5-5a**). Because the long-hydroperiod epiphyton suitability index was applied to this area, suitability was low (generally less than 0.4, **Figure 5-4a**). Model results indicated that for the current system (**Figure 5-5b**) hydroperiods in LNWR were longer than they were in the natural system due to impoundment that favors the production of epiphytic periphyton. Epiphyton suitability for the current system declined from values greater than 0.8 in the southern two-thirds of LNWR to values of less than 0.2 in the north of LNWR (**Figure 5-4b**). This was due to a hydroperiod gradient from inundation of longer than 3 years in the south of LNWR to less than 4 months of inundation in the extreme north of LNWR (**Figure 5-5b**). Hydroperiod and epiphyton suitability in the restored system were similar to that of the current system (**Figures 5-4c** and **5-5c**).

In the water conservation areas and Shark River Slough, the medium-hydroperiod floating mat periphyton suitability index was applied (**Figure 5-2**). Hydroperiods in the natural system were longer than 8 months in WCA 2, from 4 to 12 months for most of WCA 3, and longer than a year for the southernmost parts of WCA 3A and WCA 3B (**Figure 5-5a**). Floating periphyton suitability was greater than 0.8 in WCA 2 and in





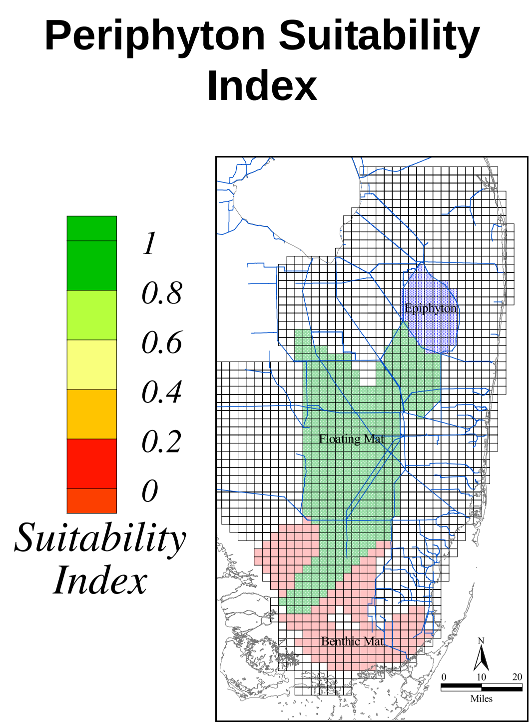


Figure 5-4. Mean annual periphyton suitability index for the a. natural system, b. current system, and c. restored system.

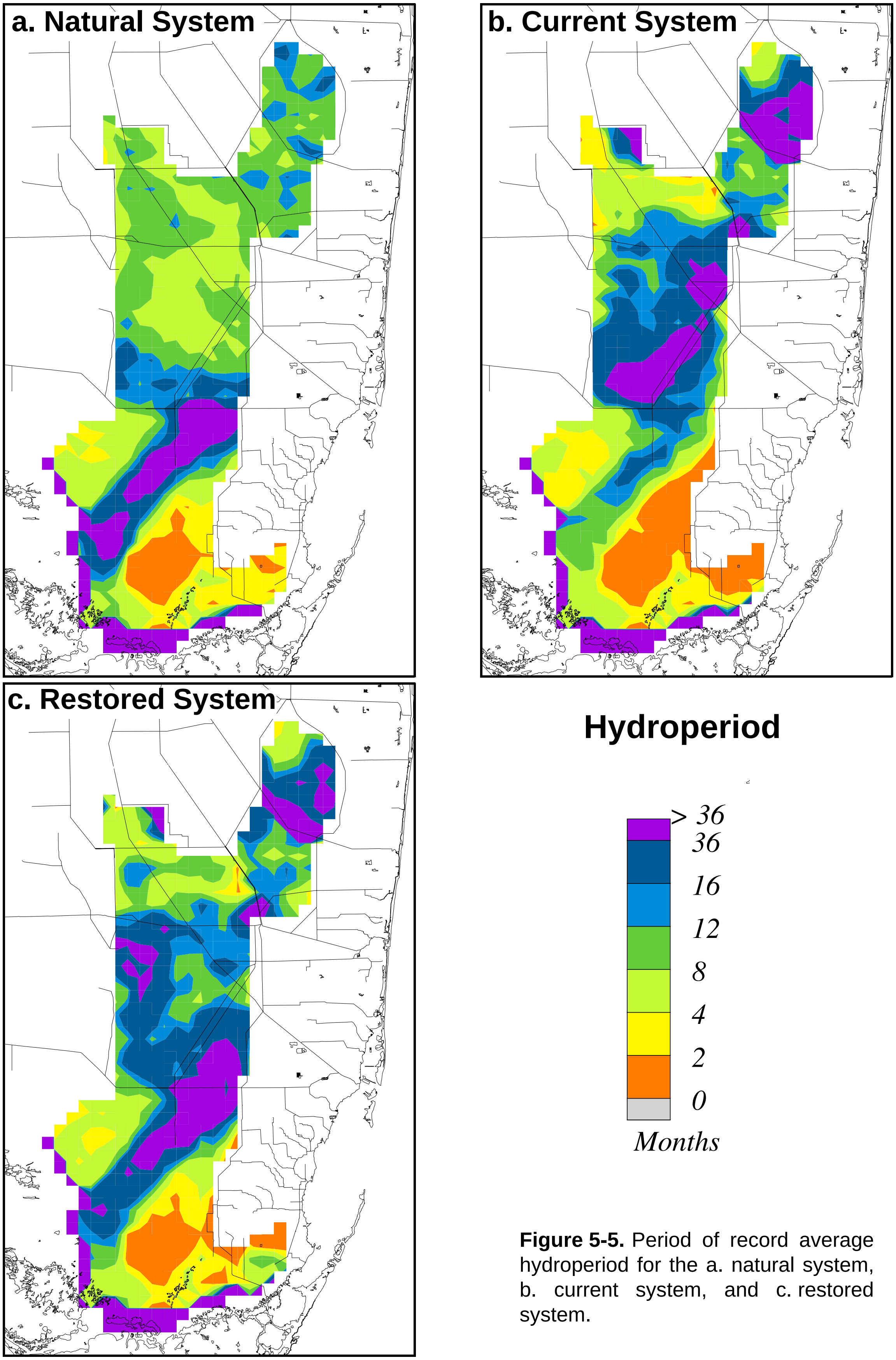


Figure 5-5. Period of record average hydroperiod for the a. natural system, b. current system, and c. restored system.

northwestern and southern WCA 3 (**Figure 5-4a**). In central WCA 3, where hydroperiods were shorter than 8 months (**Figure 5-5a**), suitability for floating periphyton declined (FPSI value from 0.6 to less than 0.2, **Figure 5-4a**). In Shark River Slough, hydroperiods, typically longer than 3 years, were unsuitable for the production of floating periphyton because they were too long (FPSI values less than 0.2, **Figure 5-4a**). However, hydroperiods of this length would tend to favor the production of epiphytic periphyton. In the current system, hydroperiods of 8 to 36 months (**Figure 5-5b**) for most of the WCA 2 and WCA 3 and Shark River Slough were suitable for the production of floating periphyton (FPSI values greater than 0.8, **Figure 5-4b**). Shorter hydroperiods (less than 8 months) in northwestern WCA 3A and longer hydroperiods (more than 2 years) in the deeper parts of WCA 3A along the L67 canal (**Figure 5-5b**) were less favorable for floating periphyton production (FPSI values less than 0.2, **Figure 5-4b**).

The benthic periphyton suitability index (BPSI) was applied to the marl prairie areas of Everglades National Park (**Figure 5-2**). Hydroperiods of 2 to 12 months in most of the marl area for the natural system (**Figure 5-5a**) resulted in high BPSI values (more than 0.8, **Figure 5-4a**). Hydroperiods and resulting benthic periphyton suitability were similar for the current and restored systems except in the extreme eastern marl area where hydroperiods of less than 2 months in the current system resulted in low PBSI values (less than 0.2, **Figure 5-4b**).

Examination of results of periphyton suitability indices as discussed in the preceding three paragraphs illustrates the usefulness of habitat suitability indices and the care that needs to be taken in applying them to specific areas. Areas with low suitability values highlight areas needing further examination of the underlying cause for the poor suitability or reassessment of appropriateness of the suitability index applied to these areas. For example, floating periphyton suitability indices that were low (less than 0.2) occurred in the natural system simulation both in drier areas (hydroperiods too short) and in wetter areas (hydroperiods too long). Application of the epiphytic periphyton suitability index to LNWR assumed a desired restoration condition supportive of long-hydroperiod epiphyton in this area. This is different from what may have been in LNWR under predrainage conditions, best simulated with the Natural System Model (NSM), which indicated shorter hydroperiods and an environment possibly better suited to the production of floating mat periphyton. Had the floating mat periphyton index been applied to LNWR, periphyton suitability values in LNWR would likely have been better in the simulated natural system than in the current or restored systems, rather than the reverse. Application of the suitability indices and careful examination of their results help focus future research efforts to reexamine restoration targets or highlight deliberate decisions to have restoration targets with hydroperiods and resulting periphyton suitability indices different from those in the natural system.

Future Research

The exercise of defining three distinct structural types of periphyton and developing and applying hydroperiod-related habitat suitability indices was a productive one. Application of the models to the natural, current, and restored systems led to the

following conclusions. Hydroperiod and water depths across the Everglades have changed to such an extent that it is inappropriate to use current hydroperiod and water depths to determine the type of periphyton model to be applied to each area or to designate boundaries between areas. Furthermore, additional research is needed to develop an accurate quantitative relationship of each structural type of periphyton to hydroperiod and other conditions. Experiments should be conducted to better document species responses to changing hydroperiod and relationships of periphyton dynamics to that of the vegetation. Taxonomic survey data should be analyzed with the goal of determining algal species hydroperiod optima and tolerances.

Periphyton production, species composition, and physical structure have been shown to vary greatly along existing and experimental phosphorus gradients (Swift and Nicholas 1987, Grimshaw et al 1993, Raschke 1993, Vzmazal and Richardson 1995, McCormick et al. 1996, McCormick and O'Dell 1996, McCormick et al. 1997, 1998, Cooper et al. 1999, Pan et al. 2000, Gaiser et al. 2001a, 2001b, 2004). Alteration in hydroperiod may change the phosphorus load. Change in water depth may affect phosphorus availability and uptake. Few experiments have examined the interaction of hydroperiod, depth, and phosphorus on ecosystem structure and function. Experiments should be conducted to determine effects of phosphorus loading on the different types of periphyton communities that occur across the system. Researchers should take advantage of “natural” experiments provided by long-term monitoring along existing phosphorus gradients where hydroperiods are being altered (or hydroperiod gradients where phosphorus is being altered).

It is also important to understand periphyton responses to the interplay of other water chemistry parameters (silica, dissolved oxygen, bicarbonate, dissolved carbon dioxide, and chloride) with hydrology because these parameters also vary across the system and may be changed with altered water delivery and hydropatterns. Finally, water flow velocity, which may also change, may have an effect on periphyton structure and composition as it does in other systems, and this effect has not been studied in the Everglades.

The Everglades is a mosaic in hydrologic, biotic, and biogeochemical terms, and its mosaic nature will have to be taken into account when designing and applying periphyton habitat suitability indices. The greatest benefit of this exercise is to elucidate the necessary focus of new periphyton research and demonstrate its potential usefulness.

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CHAPTER 6

Fish Habitat Suitability Index

Joel C. Trexler[1], William F. Loftus[2], and Kenneth C. Tarboton[3]

General Description

Fish species are primary ecosystem indicators for the Everglades. Fishes provide the food for other species, including alligators and birds. During flooding, populations of small fish (e.g., eastern mosquitofish, **Figure 6-1**), crayfish, etc., are nourished by detritus and seasonal algal growth and, because they are relatively protected in the shallow marshes from large predatory fish, they reach large numbers. During the dry period, the fish are concentrated into pools and depressions by receding waters (DeAngelis et al. 1998). The fauna of short- and long-hydroperiod areas differ: in the short-hydroperiod areas, fish and prawn densities are generally lower, whereas the crayfish density is higher (Roman et al. 1994).

Figure 6-1. Eastern mosquitofish (*Gambusia holbrooki*) is typical of small fish species found in the ridge and slough parts of the Everglades.

1. Florida International University
2. United States Geological Survey
3. South Florida Water Management District

The fish suitability index was developed based primarily on the results of studies using a 10-square foot throw trap. Sampling at this spatial scale produces results most reflective of the small-sized fishes that are numerically dominant in the Everglades (generally less than 3 inches in maximum adult length). Those species comprise the bulk of food for many wading birds and are considered an appropriate target group for assessing habitat quality in the context of food web function in this ecosystem. A different function would have been produced had our emphasis been on fish species with larger adult sizes, such as Florida gar and yellow bullheads, or game species that are important to fisherman. It was decided to not emphasize large-bodied fish species because angling is largely limited to canals and large species are rather uncommon in marshes and not often taken by wading birds.

Hydrologic Variables

Based on empirical data from freshwater marsh sampling in Everglades National Park and Water Conservation Area (WCA) 3, annual estimates of fish densities decline when water levels fall below the ground surface of the marsh for even short periods of the year (Trexler and Loftus 2001). At these times, fishes are forced into refuges that are limited in area, depth, and number. The availability of these refuges creates bottlenecks of fish population size that require several generations of unrestrained growth (prolonged period of flooding) before their influence is lost. Time-series analyses indicate that annual minimum water depth is a good measure of the effects of recent hydrologic fluctuation. It is generally correlated with other measures of hydroperiod, but explains more variation in our data than parameters such as annual average water depth (Trexler et al. 2002, 2003).

In natural refuges, such as marsh depressions and alligator ponds, the farther below ground surface the water falls, the more predation occurs, particularly among small fishes (Loftus, unpublished data; Howard et al. 1995, Kobza et al. 2004). Larger fishes suffer mortality from the effects of crowding and of low dissolved oxygen levels (Nelson and Loftus 1996). Canals are the exception in that they are deep, long linear habitats that offer refuge of differing value to fishes depending on their body size (Howard et al. 1995). Within a zone of up to approximately 1.5 miles from canals, marsh areas may be influenced by dispersal of fishes from the canals, and as such cannot be properly predicted by minimum water depth alone. Canals also accumulate large populations of large piscivorous species (relative to marshes) that may affect marsh fish densities within this zone. Such edge effects should be considered when interpreting output of this fish suitability index.

Empirical data demonstrate that the small-bodied fish component of the community requires approximately three years of constant inundation to recover fully from the effects of a dry-down (Trexler and Loftus 2001). At that point, the community characteristics of long-hydroperiod marshes regain predisturbance conditions. When the recurrence of a drydown event exceeds seven to eight years, particularly in marshes where the water levels have been kept deep and stable, the small fish component appears to decline in density, perhaps as a result of predation by larger-bodied species (Chick and Trexler, unpublished manuscript; Loftus and Eklund 1994, Kushlan 1976). The density of

fishes is dominated by hydrologic events in marshes that typically dry at a frequency of less than every three years. Thus, the shorter the hydroperiod, the lower the fish density in general, and the lower the correlation between density and time since drydown (Trexler and Loftus 2001).

A high correlation has been shown between fish density estimated from a wide range of hydroperiods in marshes in Everglades National Park and WCA 3 and a long-term average hydroperiod (Trexler and Loftus 2001). Up to a point, the longer the flooding period, the more fish per unit area are present at the site. The relationship is not linear and not monotonic. However, the maximum density of small fishes is limited at sites where hydroperiods are so long that drydown events occur less often than one per ten years. The origin of this nonlinearity is probably in the development of piscivorous fish communities in the longest-hydroperiod habitats (Chick and Trexler, unpublished manuscript). Also, this relationship disregards the effects of nutrient inputs that at low and intermediate levels also lead to increases in fish densities (Trexler and Loftus 2001, Turner et al. 1999). Aside from anthropogenic nutrient enrichment, natural variation in local nutrient availability can decrease the predictive ability of this suitability function.

Habitat Suitability Function for Fish

The fish habitat suitability function is based solely on the number of years of constant inundation since last drawdown (t in years) and is applicable to the ridge and slough landscape. The fish suitability index as a function of time since the last drawdown to dry conditions is as follows (**Figure 6-2**):

$$SI_{fish} = 1.052[1 - \exp(-0.9663(t + 0.10336)]$$

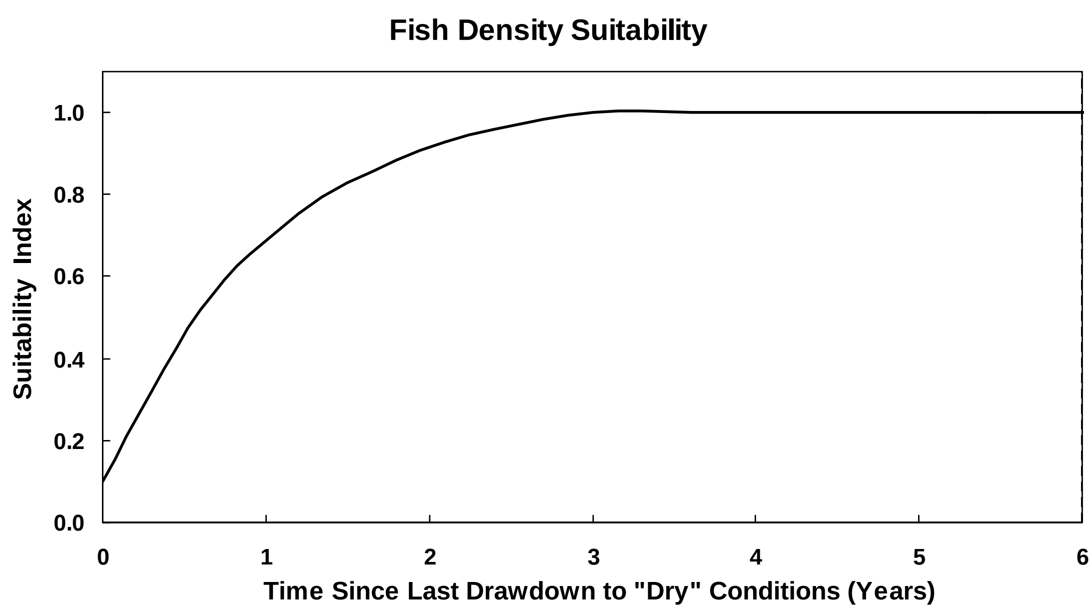


Figure 6-2. Fish suitability as a function of time of constant inundation from last drydown.

The fish suitability index above was computed from South Florida Water Management Model version 3.5 (SFWMM) and Natural System Model version 4.5 (NSM) output (31 years). The SFWMM grid cells applicable to the fish suitability index are presented in **Figure 6-3**.

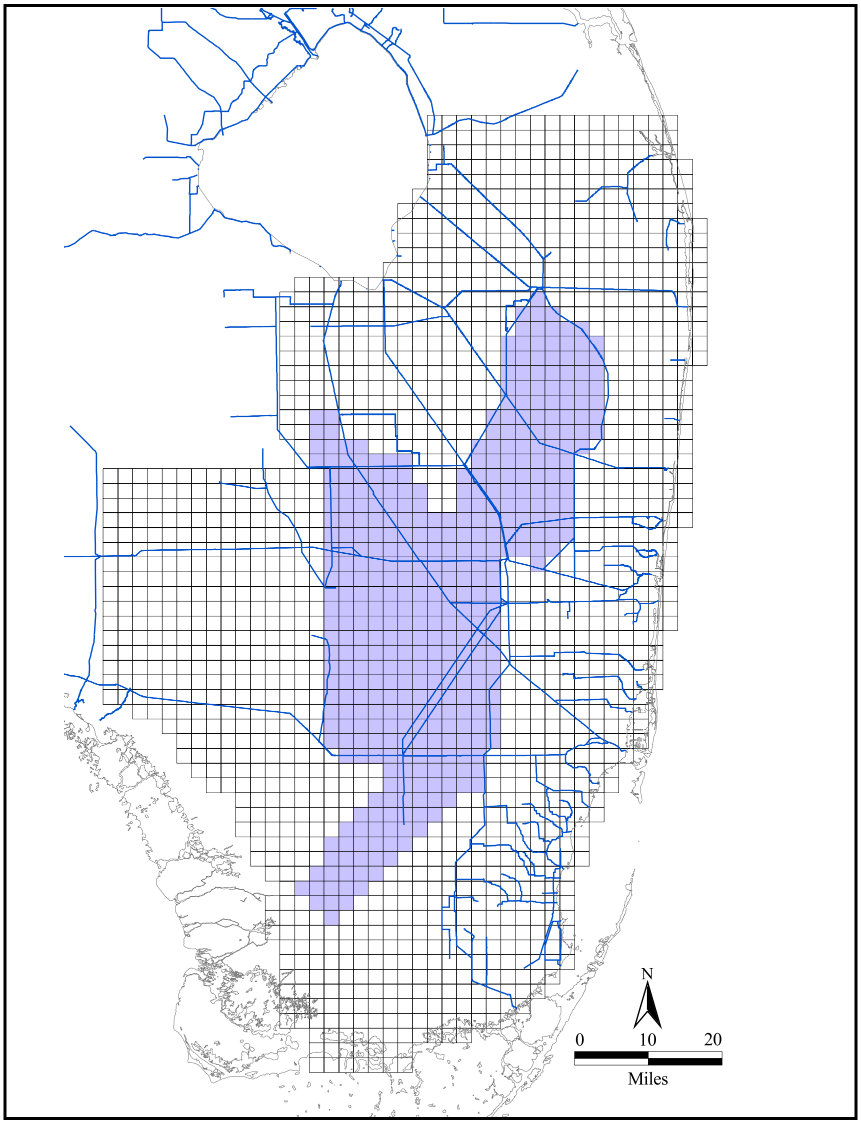


Figure 6-3. SFWMM grid cells applicable to the fish habitat suitability index.

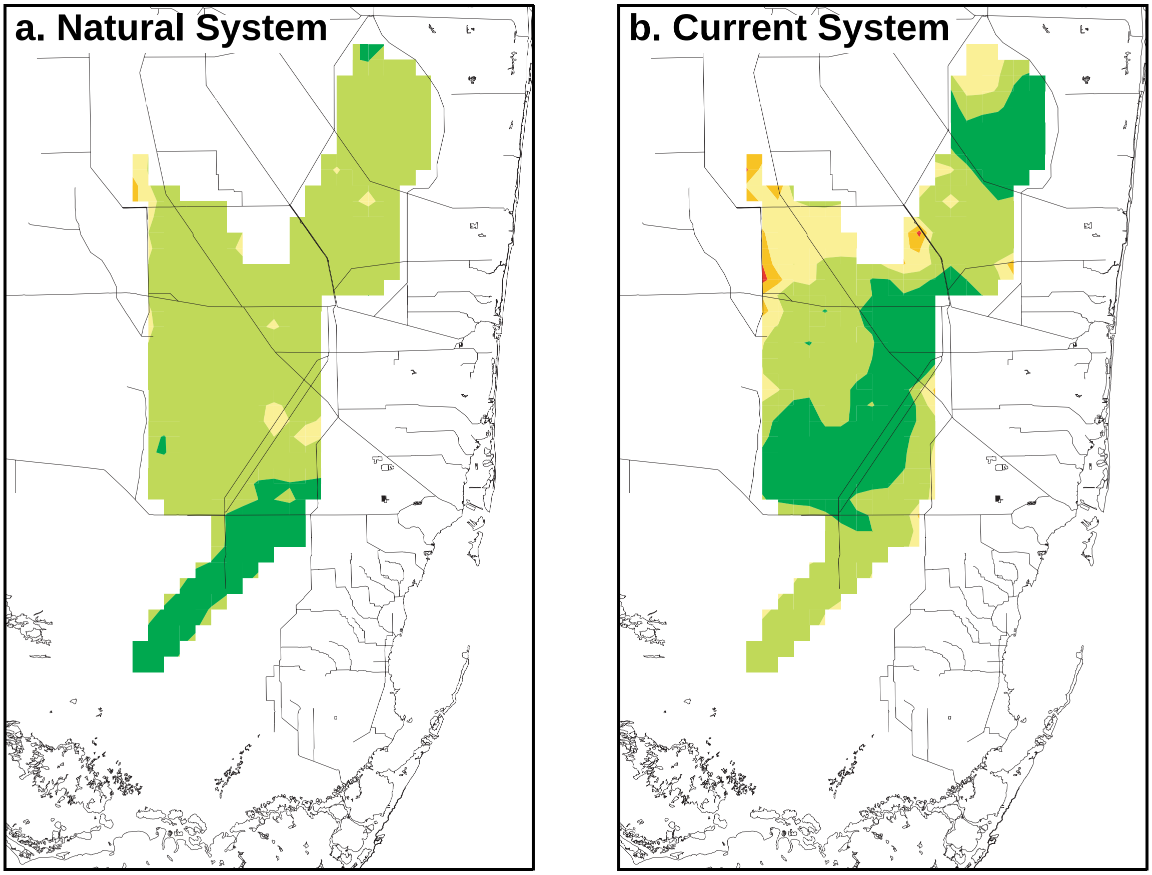
Results

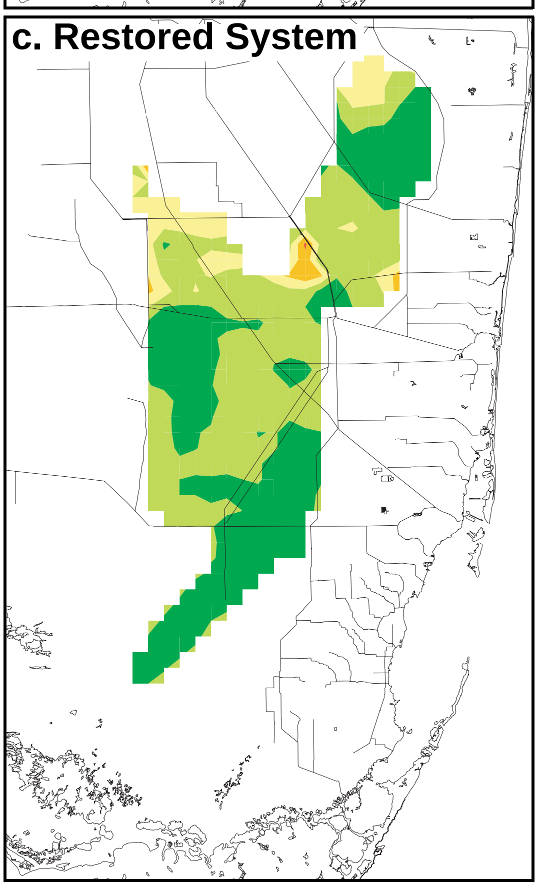
Results from the above habitat suitability function for fish should be interpreted with great care. Short-hydroperiod marshes will always appear to be "less suitable" because they naturally have lower density of fishes than long-hydroperiod marshes, though some species actually reach their maximum density in short-hydroperiod marshes. In general, however, habitats in which surface water dries each year are harsh for fishes.

But an important point is that the Everglades has always had such habitats along its margins. Thus, it would not be desirable to seek to maximize a habitat suitability index for fish across the landscape that would create an ecosystem unlike the predrainage Everglades. Rather, fish suitability should be compared to that obtained for the natural system with the goal of striving to obtaining a similar suitability distribution to that of the natural system.

Initial results indicating the performance of the fish suitability index are shown for natural, current, and restored systems in **Figure 6-4**. In the natural system (**Figure 6-4a**), the northern portion of the ridge and slough landscape is fairly well suited (0.6) to fish habitat with little effect of increased drydown at the marsh edges. Deeper water and fewer drydowns in the Shark River Slough area indicate better suitability (0.8). In the current system **Figure 6-4b**, increased drydown in the northern parts of the Arthur R. Marshall Loxahatchee National Wildlife Refuge (LWNR) and WCA 3 result in lower suitability (approximately 0.4) than in the natural system, while deeper water and fewer drydowns in the southern part of LNWR and WCA 3A to the west of the L-67 canal result in higher suitability (0.8) than in the natural system. Fish suitability in Shark River Slough is lower in the current system (0.6 to 0.8) than in the natural system. In the restored system simulation (**Figure 6-4c**), drydowns in northwestern WCA 3A are not as frequent as in the current system and the resultant fish habitat suitability is closer to that of the natural system. Some edge effects with lower fish habitat suitability occurs along the northern edge of WCA 3A and the northern parts of LNWR. Fish habitat suitability in Shark River Slough in the restored system is similar to that of the natural system, while deeper water and fewer drydowns in the central part of WCA 3A and WCA 3B result in higher fish suitability values (0.8).

Examination of results from fish habitat suitability for the natural, current, and restored system, discussed above, provides useful information that highlights areas requiring further examination and provides insights that could lead to further development of the fish habitat suitability index. Less suitable habitat at the margins of the ridge and slough landscape, not evident in the natural system simulation, is more evident in the current and restored system simulations. This may be because the fish habitat suitability index was not applied to the marginal marl prairie areas adjacent to the ridge and slough landscape in which a decline in suitability would have been evident in the natural system simulation. Alternatively, further examination of the natural system simulation or refinement of the fish suitability index may be necessary. More suitable fish habitat in the deeper impounded areas of LNWR and to the northwest of the L-67 canal in the current system, compared to the natural system, will not necessarily translate into increased small fish density in these areas because the habitat may also be more suitable to predator species. The fish habitat suitability index provides information about where habitat is potentially improved but should be used in conjunction with more complex species-specific models to provide more definitive information on expected fish densities.





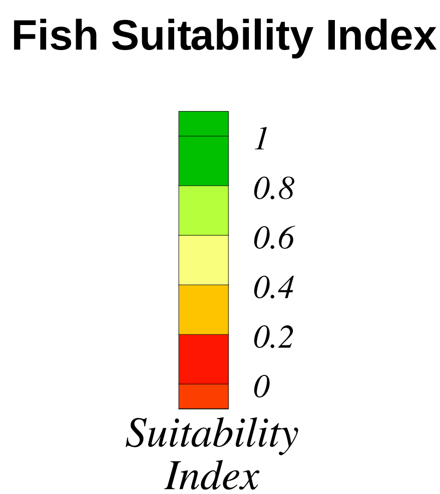


Figure 6-4. Mean annual fish suitability index for the a. natural system, b. current system, and c. restored system.

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CHAPTER 7

Alligator Habitat Suitability Index

Kenneth G. Rice[1], Frank J. Mazzotti[2], Laura A. Brandt[3], and Kenneth C. Tarboton[4]

General Description

The American alligator (*Alligator mississippiensis*; **Figure 7-1**) is not only a top consumer in South Florida, but also physically influences the system through construction and maintenance of alligator holes and trails (Mazzotti and Brandt 1994, **Figure 7-2**). The existence of this species is important to the faunal and floral character of the Everglades as it has evolved. Despite its prominence biologically and publicly in the system, many important questions about the effects of restoration on alligator populations remain unanswered.

Figure 7-1. American alligator (*Alligator mississippiensis*).

1. United States Geological Survey Center for Water and Restoration Studies
2. University of Florida, Fort Lauderdale Research and Education Center
3. United States Fish and Wildlife Service, Arthur R. Marshall Loxahatchee National Wildlife Refuge
4. South Florida Water Management District

Figure 7-2. Alligator hole and nest.

The Everglades has always been a harsh environment for alligators. Everglades alligators weigh less than alligators the same length from other parts of their range (Jacobson and Kushlan 1989, Barr 1997). Further, maximum length is decreased, and sexual maturity is delayed (Kushlan and Jacobsen 1990, Dalrymple 1996a). Jacobsen and Kushlan's (1989) model for growth in the Everglades of South Florida predicted alligators reaching a mere 4 feet in 10 years and requiring at least 18 years to reach sexual maturity. It is currently suspected that the reason for this poor condition is a combination of low food availability due to hydrologic factors (Loftus and Eklund 1994) and high temperatures (Jacobson and Kushlan 1989, Dalrymple 1996a, Barr 1997, Percival et al. 2000).

Hydrologic Variables

Hydrologic variables considered important in maintaining alligator habitat suitability include water depths and timing of specific depths relevant to breeding, nest construction, nest flooding, and suitability for survival and condition. Current water management practices have resulted in a high and unpredictable rate of alligator nest flooding. Historically, maximum water levels during egg incubation were positively correlated with water levels during nest construction. This natural predictability has been lost (Kushlan and Jacobsen 1990). Historically, alligators were abundant in marl prairie habitats of the eastern floodplain, along the edge habitats of the central sloughs. Marsh alligator densities are now highest within the remaining ridge and slough landscape and in canals and have decreased in marl marshes. Canals contain high concentrations of adult alligators. Nest densities also are relatively high on levees and associated spoil islands. Less flooding of nests occurs on these higher elevations. However, survival of young may be very low due to a decrease in the number of alligator holes or possible brood habitat proximal to canals (Chopp 2003, Rice et al. 2004). Restored hydrologic conditions might be expected to increase nesting effort, nesting success, and abundance of alligators within the marl marshes. A corresponding increase in the number and occupancy of alligator holes to serve as drought refugia for alligators and other species within the marl marshes.

Habitat Suitability Functions for Alligators

The alligator suitability index consists of four components estimated annually relating alligator life history to hydrology: suitability for breeding, suitability for nest construction, nest flooding potential within a cell, and an estimate of the impact of hydrologic condition on early age-class survival and body condition of all size classes. The four components were calculated from South Florida Water Management Model version 3.5 (SFWMM) and Natural System Model version 4.5 (NSM) output for the 2-mile by 2-mile grid cells shown in **Figure 7-3**. Many of the relationships contained in the index are based on the Across Trophic Level System Simulation (ATLSS) American Alligator Production Index Model (Palmer et al. 1998). Notably, the index discussed herein is based on a much larger scale and does not include components relating habitat and elevation to alligator population condition.

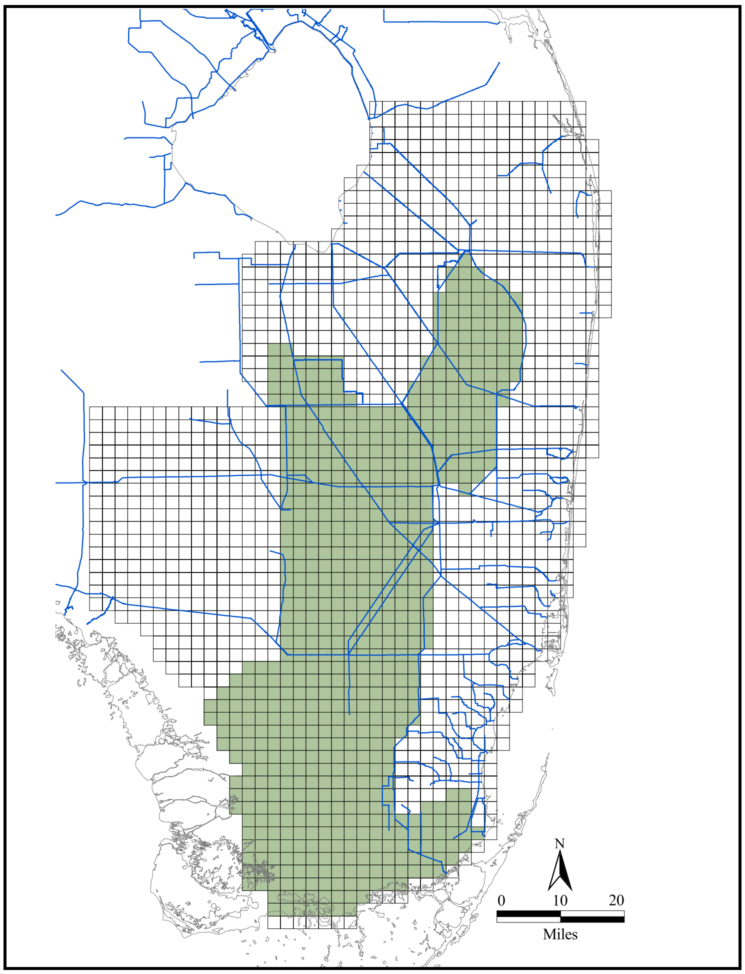


Figure 7-3. SFWMM grid cells applicable for the alligator habitat suitability index.

For calibration of the breeding, nesting, and flooding components, gross nest estimates and counts from two sources were used: systematic reconnaissance flights of Everglades National Park (S. Snow, U.S. National Park Service, personal communication)

and Florida Fish and Wildlife Conservation Commission nest counts (L. Hord, Florida Fish and Wildlife Conservation Commission, personal communication). Spatial patterns of the index for current conditions were compared with expert field observations of current alligator conditions and indices refined accordingly. For survival and condition, existing data and expert opinion on the relationships between condition, survival, and water depths were used to make expert determinations of SFWMM calibration model runs.

Breeding

Fleming (1989) developed relationships between annual water stage duration and the proportion of adult alligator females that could be expected to nest in a given year in Shark River Slough, Everglades National Park. This regression relationship was modified to reflect index values for ponding depths throughout the Everglades system. This component addresses several aspects of alligator life history: the ability of adult males to disperse for mating, physiological stress associated with drought conditions, and the prolonged follicular development in the adult female. An index value for the suitability for alligator breeding was assigned based on the number of days (t) with ponding depth below 0.5 feet from May 16 of the previous year to April 15 of the current breeding year. The index value was assigned a value of 1.0 for fewer than 50 days with ponding depth less than 0.5 feet, and decreased linearly to a value of 0.0 for more than 125 days with ponding less than 0.5 feet (**Figure 7-4**) as follows:

$$SI_{breeding} = 1.0 \qquad \text{for } t \le 50 \text{ days}$$

$$SI_{breeding} = (125 - t)/75 \qquad \text{for } 50 < t \le 125 \text{ days}$$

$$SI_{breeding} = 0.0 \qquad \text{for } t > 125 \text{ days}$$

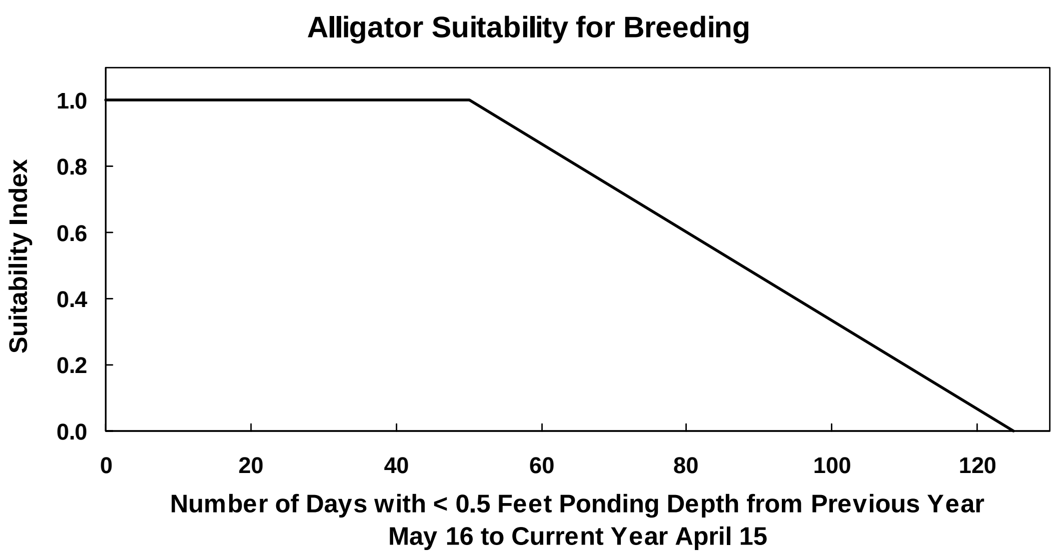


Figure 7-4. Alligator suitability for breeding as a function of the number of days with ponding depth below 0.5 feet from May 16 of the previous year to April 15 of the current year.

Nest Construction

In Everglades National Park, a significant relationship has been noted between alligator nesting effort and average water depth during the peak mating season from April to May (Fleming 1989, 1990). Regression analysis was used to examine the relationship between nest estimates from systematic reconnaissance flights of Everglades National Park (S. Snow, U.S. National Park Service, personal communication) and water depth in Shark River Slough. These relationships were used to develop the following component index by modification to reflect deeper water depths elsewhere in the system. The suitability of an area for alligator nest construction was defined by using the mean water depth (d) from April 15 to May 15. Minimum index values (0.0) were assigned at mean depths less than 0.0 feet and more than 4.0 feet. Maximum values (1.0) were assigned at mean depths of 1.3 to 1.6 feet (**Figure 7-5**):

$$SI_{\text{nest construction}} = 0.0 \qquad \text{for } d \leq 0.0 \text{ or } d > 4.0 \text{ feet}$$

$$SI_{\text{nest construction}} = d/1.3 \qquad \text{for } 0.0 < d \leq 1.3 \text{ feet}$$

$$SI_{\text{nest construction}} = 1.0 \qquad \text{for } 1.3 < d \leq 1.6 \text{ feet}$$

$$SI_{\text{nest construction}} = (4.0 - d)/2.4 \qquad \text{for } 1.6 < d \leq 4.0 \text{ feet}$$

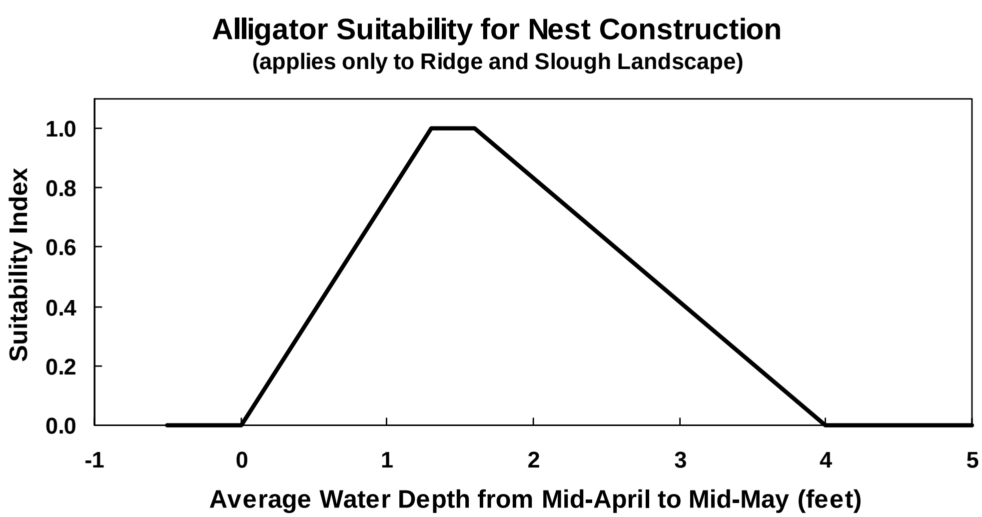


Figure 7-5. Alligator suitability for nest construction as a function of the average water depth during the peak nesting season (April 15 to May 15).

Nest Flooding

Alligator nests are generally constructed during late June to early July in south Florida (Kushlan and Jacobsen 1990). Once the nest has been constructed, any rise in water level can result in flooding of the clutch cavity and egg mortality. The lowest eggs in the clutch cavity rest 0.5 to 1.0 feet from the water surface during nest construction for WCA 2 and 3 (K.G. Rice, U.S. Geological Survey, unpublished data) and Everglades

National Park (Kushlan and Jacobsen 1990). The total clutch cavity also is 0.5 to 1.0 feet in depth. Therefore, after nest construction, a rise in water level of around 0.5 feet will begin to result in egg mortality with total mortality of the clutch occurring after a rise of 1.0 to 1.5 feet. A notable exception exists in central Arthur R. Marshall Loxahatchee National Wildlife Refuge (LNWR) where many nests are constructed on tree islands and are much less likely to flood (Brandt and Mazzotti 2000). Therefore, cells in central LNWR are assigned a value of 1.0 for the nest flooding component.

For the remainder of the area to which alligator suitability indices were applied, the nest flooding component was established by subtracting the mean water depth during nest construction (June 15 to July 1) from the maximum water depth during egg incubation (July 1 to August 31) to obtain the maximum water depth above the mean (June 15 to July 1) water depth (Δ_{max}). Differences of up to 0.5 feet were assigned an index value of 1.0 and the index decreased linearly to a value of 0.0 for depth difference larger than 1.5 feet (**Figure 7-6**):

$SI_{nest\ flooding} = 1.0$ for $\Delta_{max} \leq 0.5$ feet

$SI_{nest\ flooding} = 1.5 - \Delta_{max}$ for $0.5 < \Delta_{max} \leq 1.5$ feet

$SI_{nest\ flooding} = 0.0$ for $\Delta_{max} > 1.5$ feet

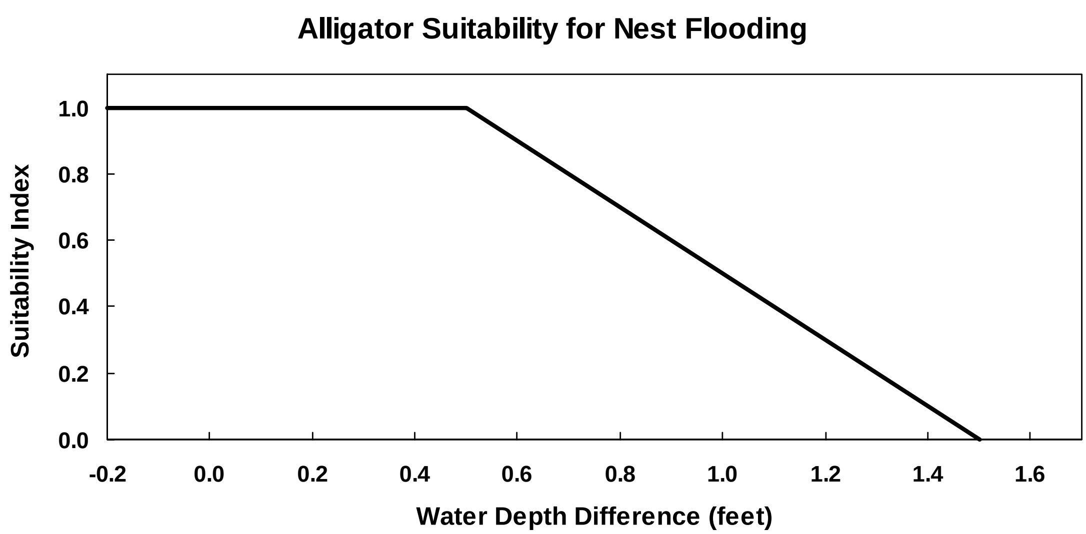


Figure 7-6. Alligator suitability for nest flooding (proportion of alligator nest not flooded) as a function of the maximum water depth difference between the average for June 15 to July 1 and the maximum water depths from July 1 to August 31.

During calibration, it was noticed that this component did not perform during certain low water periods. During nest construction several regions had water depths below the ground surface and, thus, when water levels rose just to the ground surface, the index would predict flooding. Therefore, the index was adjusted to reflect that flooding would only begin, in these cases, when water depths increased to 0.5 feet above ground surface.

Survival and Condition

Cannibalism by larger alligators and predation by other species on early age-class alligators is well established (Dalrymple 1996a, Delany and Abercrombie 1986). As water depths decrease to surface levels during extreme dry periods, alligators are concentrated in alligator holes and other depressions. In general, alligator holes are occupied by large adult animals (100 percent occupancy by adult alligators in holes greater than 15 feet diameter, F. Mazzotti, University of Florida, unpublished data, Percival et al. 2000) but also are the final dry season refugia for smaller size classes. Therefore, as water levels decrease below surface, cannibalism by large adults on smaller age/size classes increases. Survival of early age-class animals is thus affected by hydrology.

This concept is incorporated into an early age class survival index component with a value of 1.0 for average water levels in the 2-mile by 2-mile SFWMM grid cells (**Figure 7-3**) above -0.5 feet. Microtopographic variations within model grid cells result in some ponded water for an average grid cell depth of -0.5 feet, particularly in alligator holes. The index decreases linearly for average water depths below -0.5 feet to a value of 0.0 at -2.0 feet (**Figure 7-7**).

Body condition of all size-classes is known to decrease with an increase in water depth above a certain threshold value (Barr 1997, Dalrymple 1996a, 1996b). Observed condition values (K. Rice, U.S. Geological Survey and F. Mazzotti, University of Florida, unpublished data) and expert opinion were used to assign a value of 1.0 at average grid cell water depths below 0.75 feet in a body condition index component. The index decreases linearly to a value of 0.2 at 3.0 feet and greater average depths (**Figure 7-7**).

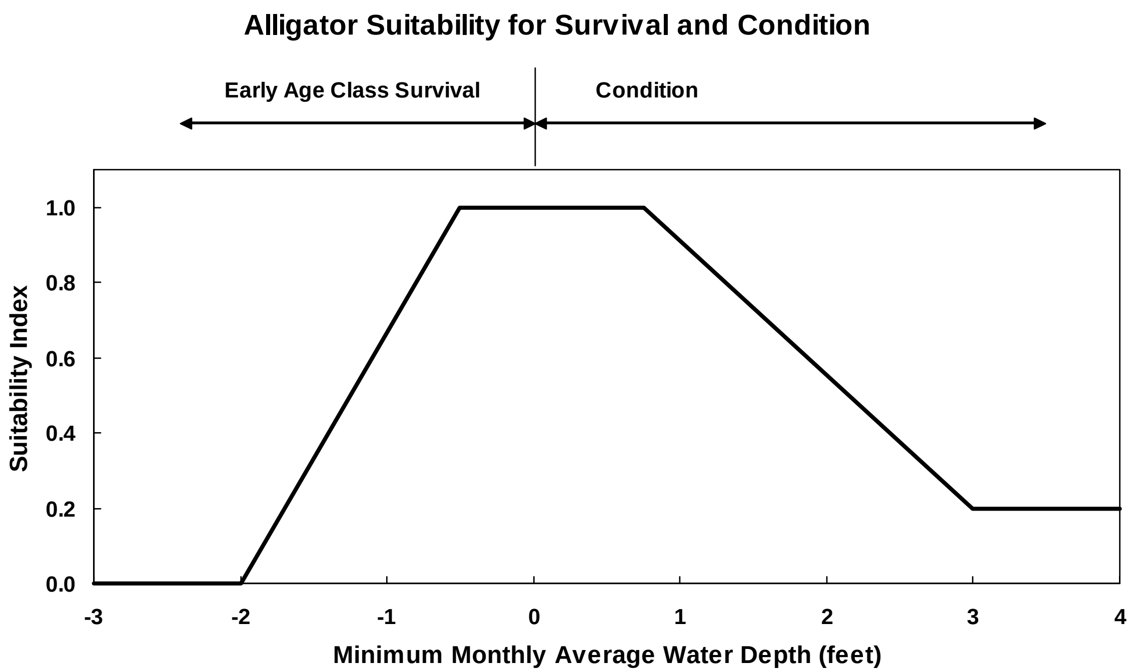


Figure 7-7. Alligator suitability for survival and condition as a function of the minimum monthly average water depth.

The early age class survival and body condition index components were combined into a single index (**Figure 7-7**), since one reflected response to below ground surface water levels and the other above ground surface water depths. The final metrics for each component were developed through consultation with a panel of crocodilian experts from south Florida and examination of different model runs including the SFWMM version 3.5 calibration and verification runs representing the best estimate of actual hydrologic conditions from 1973 to 1989 and 1990 to 1995, respectively. The minimum of the 12 monthly average (from daily model output) water depths (d in feet) was used to define a suitability index for each year as follows:

$SI'_{survival\ and\ condition} = 0.0$ for $d \leq -2.0$ feet

$SI'_{survival\ and\ condition} = (d + 2.0)/1.5$ for $-2.0 < d \leq -0.5$ feet

$SI'_{survival\ and\ condition} = 1.0$ for $-0.5 < d \leq 0.75$ feet

$SI'_{survival\ and\ condition} = (2.85 - 0.8d)/2.25$ for $0.75 < d \leq 3.0$ feet

$SI'_{survival\ and\ condition} = 0.2$ for $d > 3.0$ feet

Since recovery from a catastrophic drought would take several years, the final survival and condition index is defined as a function of the above index as follows:

$$SI_{survival\ and\ condition} = SI'_{survival\ and\ condition} * (\text{number of years since last drydown to} < 0.3 \text{ feet})/3$$

where the number of years since last drydown to less than 0.3 feet of water depth is limited to a maximum of 3 years.

Overall Alligator Suitability

A weighted arithmetic mean of the above subindices is used to calculate the composite alligator index value. Each of the component values is weighted based on the quantity and quality of data and expert opinion on each component. In general, components for which there was more data and less uncertainty were given higher weights. The breeding and nesting components appear to more adequately describe these stages in alligator life throughout the Everglades ecosystem. Therefore, breeding and nesting components were each assigned the highest weight of 3 in compilation of the composite index value. Due to the influence of local habitat factors and elevation, the nest flooding component contained more uncertainty, and was therefore assigned a weight of 2.0. The survival and condition index component contained the greatest amount of uncertainty, and was therefore assigned a weight of 1. The overall alligator suitability index (ASI) is thus defined as follows:

$$ASI = (3*SI_{breeding} + 3*SI_{nest\ construction} + 2*SI_{nest\ flooding} + SI_{survival\ and\ condition})/9$$

The composite index was applied to the remnant Everglades as shown in **Figure 7-3**. However, data used in defining the component subindices indicate that the composite index would be most appropriate for use in the central slough regions of the Everglades. Peripheral marl prairie regions (see **Figure 3-1**) may have index values that are skewed due to different relationships between alligator population ecology and hydrology. The flooding component should not be used in central LNWR since many alligators nest on tree islands reducing the probability of nest flooding. Hence, model grid cells in LNWR are assigned a value of 1.0 for the nest flooding component.

Part of the calibration and evaluation process involved comparing the results of each index associated with the simulated hydrology of the natural, current, and restored systems. The next section shows the results of these comparisons for each of the four separate indices and for the combined index.

Results

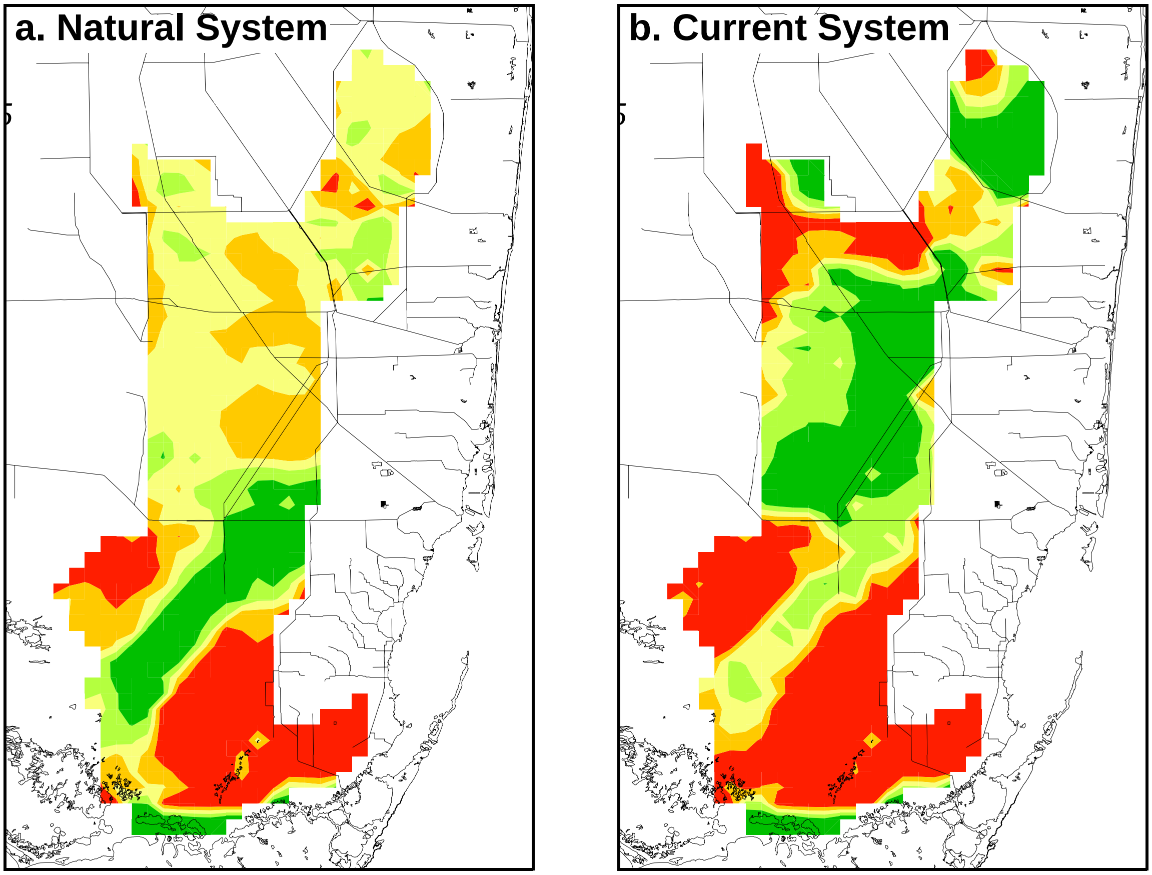
Results of applying the alligator indices to model output from the natural, current, and restored system simulations are discussed for the individual subindices and then for the overall composite index.

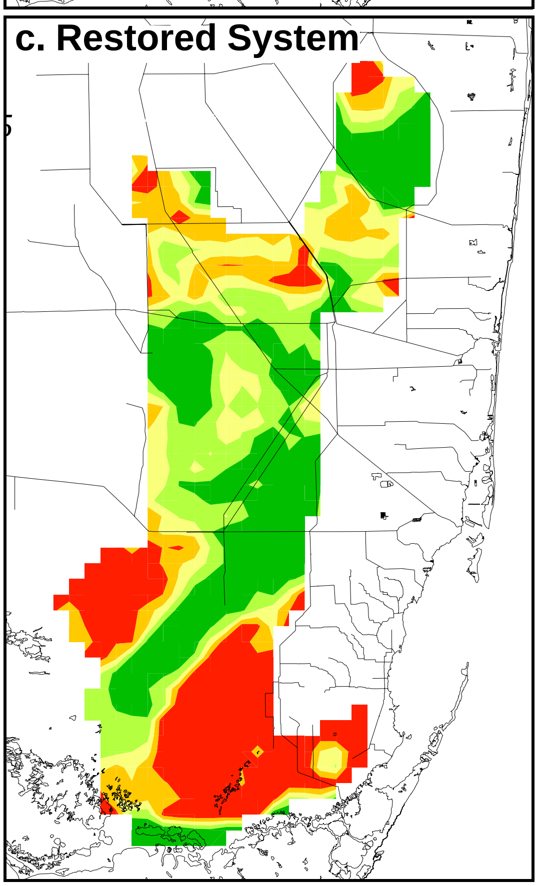
Breeding

Breeding index scores for the natural system (**Figure 7-8a**) are high in Shark River Slough (> 0.8) and marginal (0.2 to 0.6) over most of the water conservation areas. Since the breeding index was developed from observations of annual water stage and the proportion of adult females nesting in Shark River Slough, it appears to work well for the slough areas. Historical information (Craighead 1968) indicates that edge habitats had the highest numbers of alligators and not the deep sloughs. However, because this index is applied at a 2-mile by 2-mile scale, it may not be able to indicate the suitability of important breeding areas, such as alligator holes, in the edge prairies.

In the current system (**Figure 7-8b**), the highest index values for breeding habitat are located in the deeper parts of WCA 3A to the northwest of the L-67 canal and in the southern two-thirds of LNWR. Low breeding suitability occurs in the drier areas of northern WCA 3A, WCA 2A and the northern third of LNWR as well as in the marl prairie areas of Everglades National Park (see **Figure 3-1**). These results tend to support the argument above that suitable alligator breeding habitat has decreased with drainage and anthropogenic modification of the system. Although breeding suitability in Shark River Slough in the current system is high (0.4 to 0.8) relative to the flanking marl marshes, it is lower than in the natural system.

In the restored system (**Figure 7-8c**), breeding suitability in Shark River Slough is restored to match that of the natural system (> 0.8), and suitability is high (0.6 to 1.0) for alligator breeding in much of WCA 3A and WCA 3B south of Alligator Alley. Suitability for breeding in the southern portion of LNWR is also high, similar to the current system.





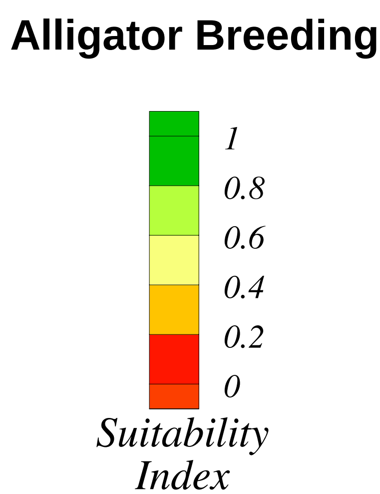


Figure 7-8. Mean annual alligator suitability index for breeding for a. the natural system, b. the current system, and c. the restored system.

Nest Construction

Nest construction suitability is low in the marl prairie areas at the edges of the ridge and slough landscape for natural, current, and restored system simulations (**Figure 7-9**). Low nest construction suitability (0.0 to 0.4) is also evident throughout the water conservation areas and LNWR for the natural system (**Figure 7-9a**). Relatively high suitability indices (0.6 to 0.8) for nest construction in the natural system occur in portions of northeastern Shark River Slough. The component index optimum of 1.3-1.6 feet may be high for areas north of Shark River Slough.

In the current system (**Figure 7-9b**), nest construction suitability indices are lower in northwestern WCA 3A, northern LNWR and Shark River Slough than in the natural system, while southern LNWR and portions of WCA 3A to the northwest of the L-67 canal have higher nesting suitability indices (0.6 to 0.8) than in the natural system.

The restored system has high (> 0.8) nesting suitability in northeastern Shark River Slough, similar to that of the natural system; however, in the restored system the high nesting suitability extends to cover much of WCA 3B (**Figure 7-9c**). Nesting suitability in WCA 3A south of Alligator Alley, in parts of WCA 2B, and in southern LNWR, is higher in the restored system than in the natural system, while suitability in northern LNWR is lower than in the natural system.

The overall relatively low nesting suitability for the natural, current, and restored systems tends to indicate that the nesting suitability index may be a little too narrowly defined in terms of the range of conditions that would indicate ideal conditions for nesting. Closer investigation of the index indicates that water depths between 1.3 and 1.6 feet from mid-April to mid-May would produce a suitability of 1.0 while average water depths between 0.7 and 2.8 feet (a range of over 2 feet) within the same time period would produce suitability values greater than 0.5. At the coarse scale (2-miles by 2-miles) at which the alligator nesting suitability index is applied, variables such as microtopographic elevation differences, vegetation types, and tree islands, which may all effect suitability for nesting, are not considered. This index merely compares estimates of overall suitability and is appropriate for making comparisons among scenarios rather than making absolute predictions of nest construction suitability.

Nest Flooding

Nest flooding suitability is high (i.e., low likelihood of flooding nests) for almost the entire remnant Everglades in the natural system simulation (**Figure 7-10a**). Slightly lower suitability occurs in the current system in WCA 3A and most of WCA 2 (**Figure 7-10b**). Only in the southwestern part of WCA 2A and the south of LNWR is nest flooding suitability less than 0.6 in the current system. Recall that the nest flooding index specifies a value of 1.0 for central LNWR because of the tendency for alligators to construct nests on tree islands in this area. Nest flooding suitability in the restored system (**Figure 7-10c**) is only less than a value of 0.6 in southern LNWR and parts of WCA 3A to the northwest of the L-67 canal.

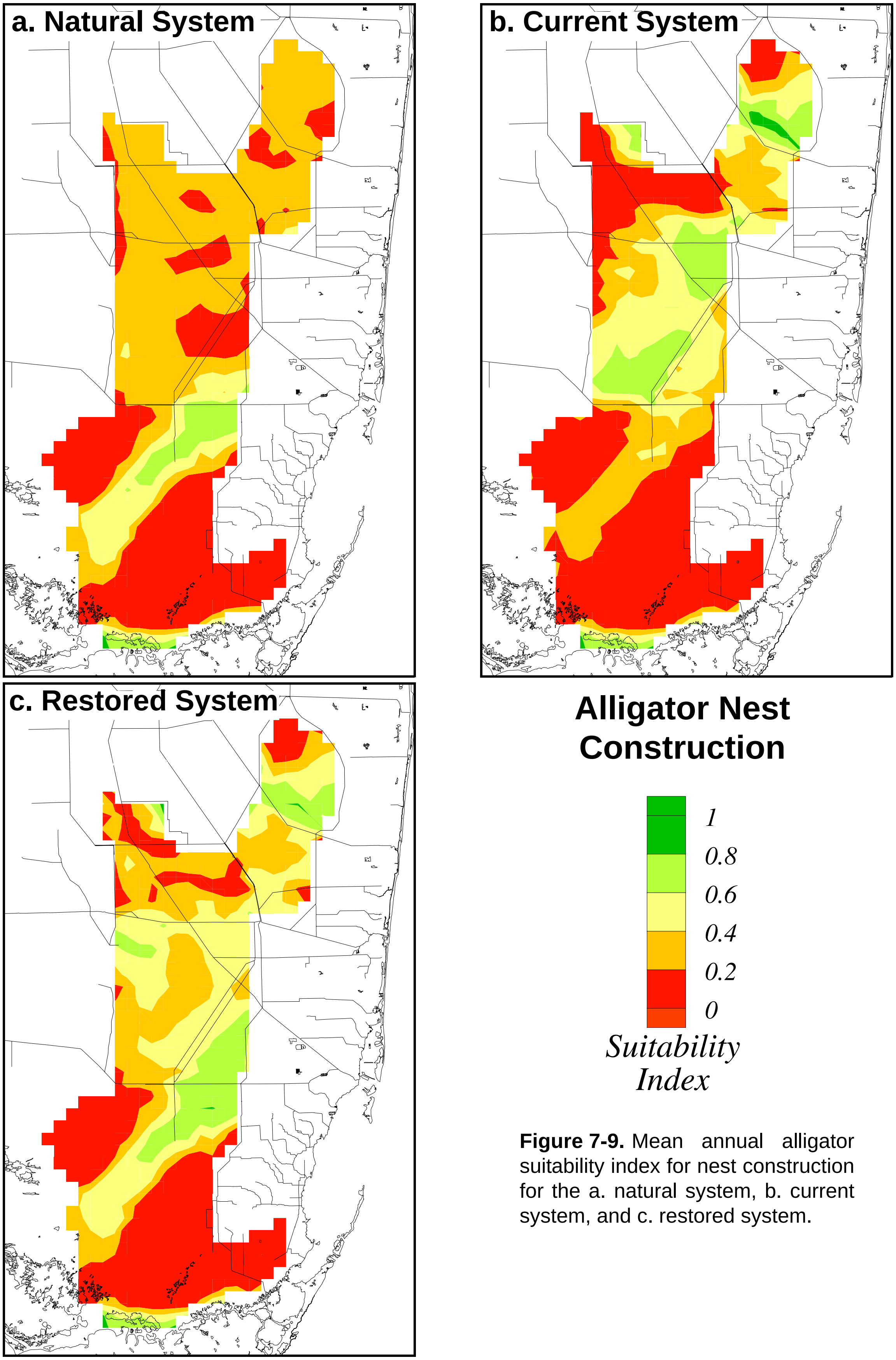


Figure 7-9. Mean annual alligator suitability index for nest construction for the a. natural system, b. current system, and c. restored system.

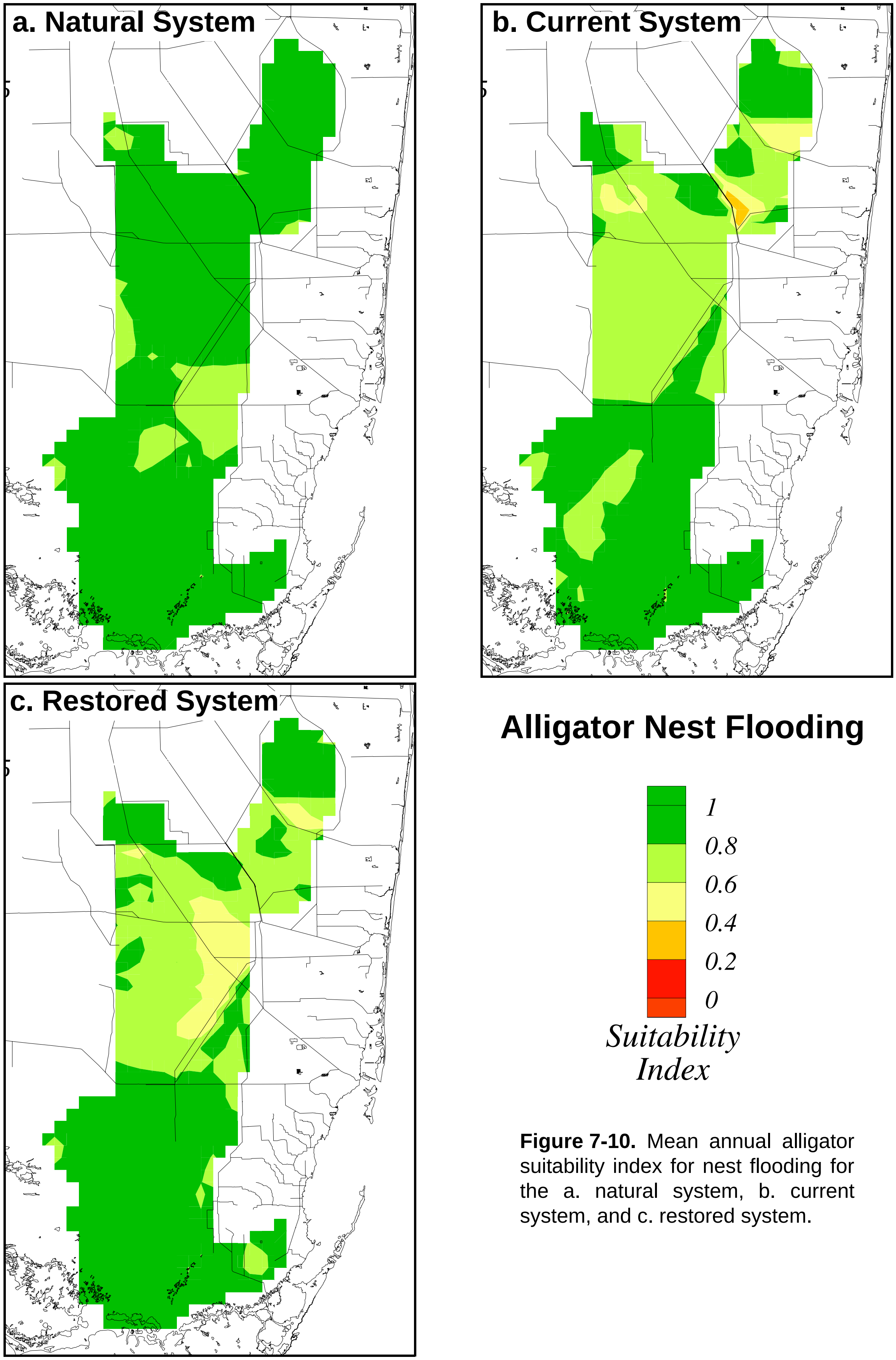


Figure 7-10. Mean annual alligator suitability index for nest flooding for the a. natural system, b. current system, and c. restored system.

In general, the nest flooding suitability index, as specified, is fairly insensitive to hydrologic differences between the natural, current, and restored systems. Perhaps average cell (2-mile by 2-mile) water depth difference may not be the most appropriate metric to define nest flooding suitability because it does not consider microtopography. Data from particular years in which heavy flooding of nests has occurred could be used to refine this index.

Survival and Condition

Alligator early age/class survival and condition suitability (**Figure 7-11**) has very similar results to those of the nest construction suitability (**Figure 7-9**). Survival and condition suitability is low in the marl prairie areas at the edges of the ridge and slough landscape for natural, current, and restored system simulations (**Figure 7-11**). Low survival and condition suitability (0.0 to 0.4) is evident throughout the water conservation areas and LNWR for the natural system (**Figure 7-11a**). Shark River Slough has moderate survival and condition suitability (0.4 to 0.6) in the natural system.

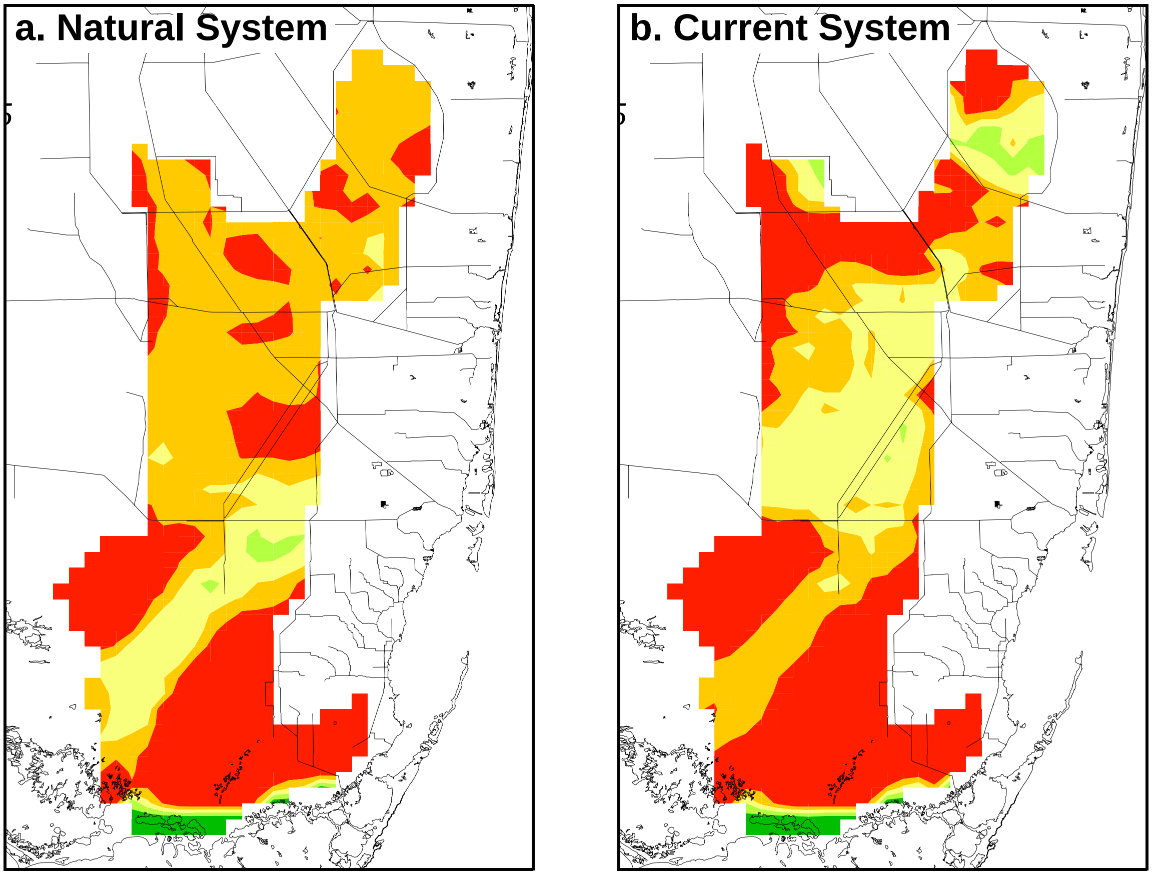
In the current system (**Figure 7-11b**), survival and condition suitability is worse in northwestern WCA 3A, northern LNWR, and Shark River Slough than in the natural system, while southern LNWR, portions of WCA 3A south of Alligator Alley, and WCA 3B have better survival and condition suitability (0.4 to 0.6) than in the natural system.

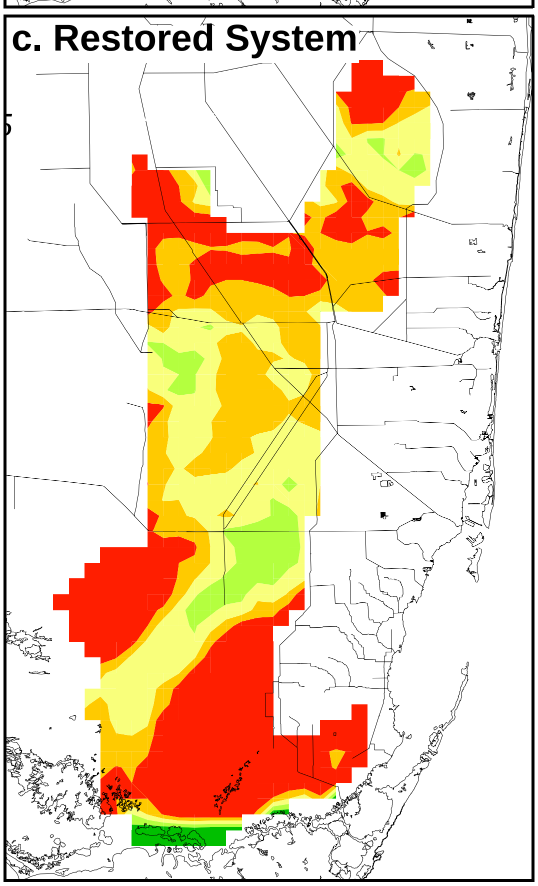
The restored system (**Figure 7-11c**) has relatively high (0.6 to 0.8) survival and condition suitability in northeastern Shark River Slough and higher suitability values (0.4 to 0.6) than the natural system in much of WCA 3A south of Alligator Alley, WCA 3B, and southern LNWR. Survival and condition suitability in the northern LNWR is lower than in the natural system.

The overall relatively low survival and condition suitability for the natural, current, and restored systems supports earlier discussion that the Everglades is a relatively harsh environment for alligators. However, it should be noted that since this index had the greatest amount of uncertainty and was assigned the lowest weight, it has the smallest effect on the composite alligator suitability index.

Overall Alligator Suitability

Overall alligator suitability in the natural system (**Figure 7-12a**) is relatively high (0.6 to 0.8) in Shark River Slough, moderate (0.4 to 0.6) for most of the water conservation areas and low (< 0.4) in the marl prairie areas on the edges of Shark River Slough. In the current system (**Figure 7-12b**), overall alligator suitability is lower in Shark River Slough, northern WCA 3A and northern LNWR than in the natural system. Overall alligator suitability in the current system is higher in WCA 3A south of Alligator Alley and southern LNWR than in the natural system. In the restored system (**Figure 7-12c**), overall alligator suitability is higher in northeastern Shark River Slough, WCA 3B, parts of WCA 3A, and southern LNWR than in the natural system, while it is slightly lower than the natural system in northern LNWR.





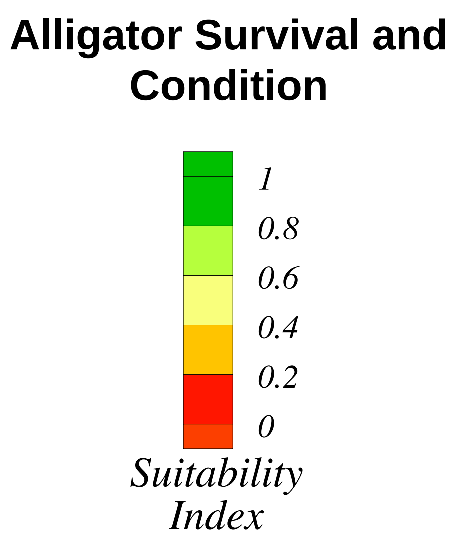


Figure 7-11. Mean annual alligator suitability index for survival and condition for the a. natural system, b. current system, and c. restored system.

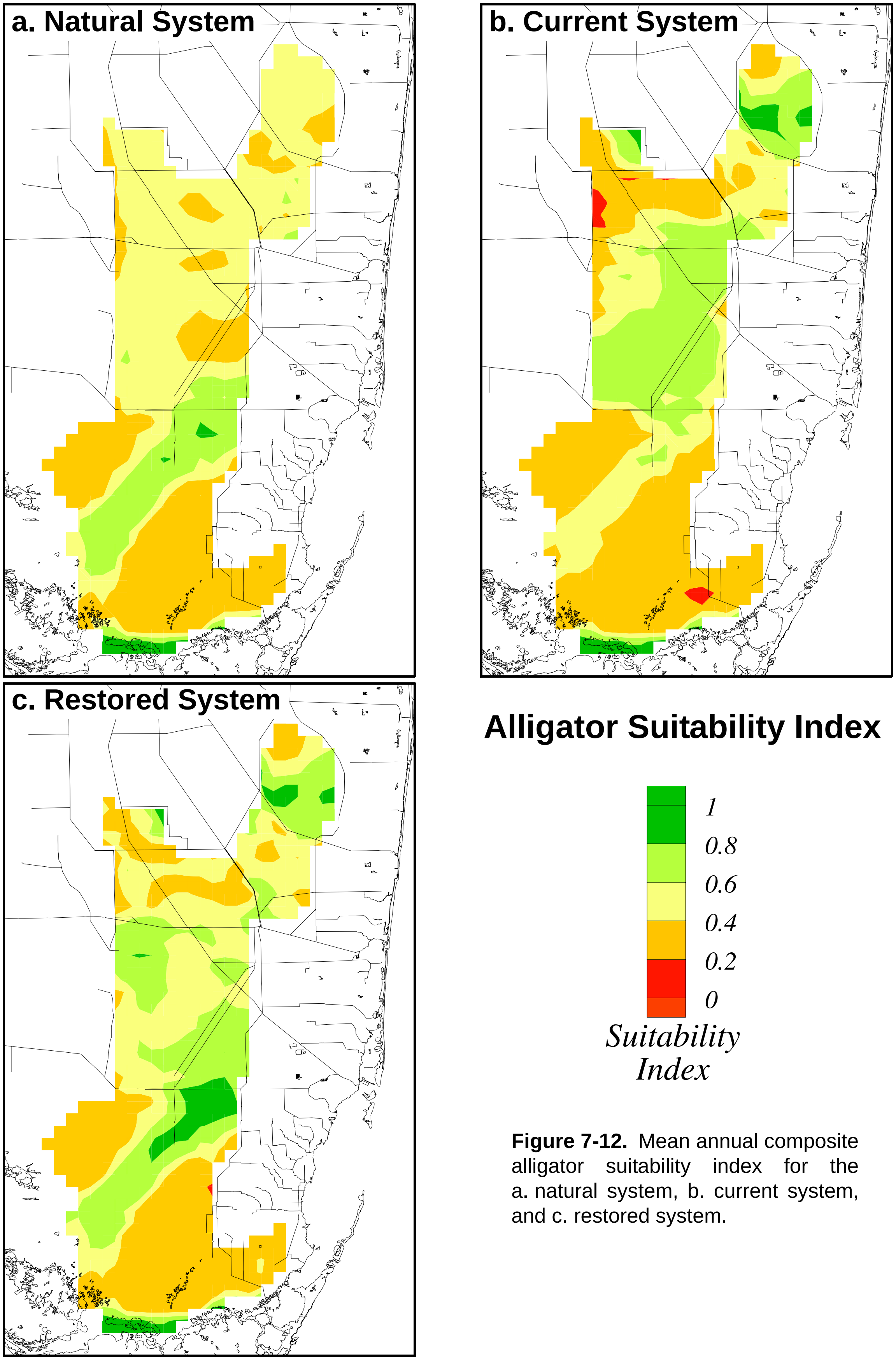


Figure 7-12. Mean annual composite alligator suitability index for the a. natural system, b. current system, and c. restored system.

The overall alligator suitability reflects spatial suitability patterns most similar to those of the nest construction suitability index with some noticeable influence from the breeding index. The nesting and breeding indices have the highest weights, and results of the survival and condition index were similar to those of the nest construction index so did not noticeably influence the overall alligator index. Similarity between the nest construction and survival and condition indices may be because the minimum monthly average water depth, used in the survival and condition index, usually occurs at about the same time as the nest construction period of mid-April to mid-May at the end of the dry season.

Although the nest flooding index is almost uniform throughout the entire domain, and has relatively lower weighting than the nesting and breeding indices, it has the effect of moderating the overall alligator index so that the lowest overall index values, except in a few isolated cases, do not fall below a value of 0.2. Combination of the component indices also limits the upper end of the overall alligator suitability index to a value of 0.8, except again in a few isolated areas.

Due to the similarity between the more sensitive alligator index components and the lower weighting of the less sensitive nest flooding index, an area for future alligator suitability index development could be simplification of the component subindices into a single index that has a broader range of values than the current overall suitability index. In general, increases in the alligator populations expected in edge habitat such as the marl marshes are not reflected in these alligator habitat suitability indices. The scale (2-mile by 2-mile) is too course to capture microtopographic variation such as alligator holes, animal tracks, and tree islands. Additional field information, such as the estimation of the density of refugia per cell, could be used to enhance the alligator suitability index, particularly the early age class survival subindex. Further, since most components of the index were developed using data from Shark River Slough, the application of the index throughout the Everglades system must be for comparisons of relative effects of alternatives only. The ecological and hydrologic relationships used in the index may not accurately describe populations outside of Shark River Slough. The alligator suitability index, as presented herein, still provides valuable information for relative comparisons between modeled water management alternatives.

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CHAPTER 8

Wading Bird Habitat Suitability Index

Dale E. Gawlik[1], Gaea Crozier[2], and Kenneth C. Tarboton[2]

General Description

The sustainability of healthy wading bird (**Figure 8-1**) populations is a primary goal of Everglades restoration. Our understanding of the response of wading birds to hydrologic conditions has also been used to establish hydrologic targets for restoration. Over time, the response by wading birds will play a prominent role in assessing the progress of restoration.

Figure 8-1. Wading birds: top is a white ibis, bottom left is a wood stork, and bottom right is a little blue heron.

1. Florida Atlantic University

2. South Florida Water Management District

Both empirical data and simulation models have been used to evaluate the effect of restoration scenarios on wading birds or wading bird habitats. The modeling approaches include a complex individual-based behavior model (i.e., ATLSS, http://www.atlas.org; Fleming et al. 1994, DeAngelis et al. 1998) and a simpler index model (Curnutt et al. 2000). Both modeling approaches were spatially explicit and assumed that, all things being equal, habitat suitability increased as a function of fish population size, either directly in the case of Across Trophic Level System Simulation (ATLSS) or indirectly in the index model.

Hydrologic Variables

Hydrologic variables considered important for wading bird suitability are depth and the drying process or recession rate that affects fish availability. Several modeling approaches have been developed to relate wading bird habitat suitability to fish population size either directly or indirectly. Observations show that fish populations are much higher in marshes that are continuously inundated than in areas that dry out regularly (Loftus and Eklund 1994). Therefore, in these models, fish population size increases as a function of time since drying of the marsh. However, there is a distinction between processes that increase overall fish population size and those that produce high densities of fish in small patches at the scale at which wading birds are feeding. During much of the year when fish are being produced, water depths are too deep to allow birds access to them. The ideal feeding conditions for wading birds occur when the marsh surface is almost dry and fish are experiencing high mortality (W. Loftus, personal communication). From a bird's perspective, it is more important that conditions for high fish mortality occur than conditions for high fish production. Fish populations rebound quickly following a drydown, but most importantly, receding water levels during the dry season, overlaid on small depressions in the marsh surface, produce small patches of shallow water with exceedingly high concentrations of fish; many times higher than densities due to prolonged hydroperiod. During a seasonal drydown, fish concentrations increased by a factor of 20 to 150 in the Everglades and Big Cypress National Preserve (Carter et al. 1973, Loftus and Eklund 1994, Howard et al. 1995). Thus, the density of fish within food patches is overwhelmingly affected by the physical process of drying.

Patches of concentrated prey are typically shallow with sparse vegetation, making individual fish more vulnerable to capture and increasing wading bird feeding success (Kushlan 1976a). Although these high-density food patches may be scattered in the landscape, wading birds have adaptations such as white plumage and social foraging that allow them to minimize their search time (Kushlan 1981, Erwin 1983). Thus, at the landscape scale, wading birds are able to exploit small patches of highly available prey and large foraging aggregations indicate good feeding conditions. Species such as wood storks, white ibises, and snowy egrets appear to be more dependent, than are other wading bird species, on high-density food patches to have high reproductive output (Gawlik 2002). Hydrologic patterns that produce the maximum number of these patches with high prey availability (i.e., high water levels at the end of the wet season and low water levels at the end of the dry season) tend to produce good nesting effort for these species (Smith and Collopy 1995) and are consistent with predictions from experimental studies (Gawlik

2002). A shift in the location of wading bird nests from the coastal to the interior Everglades over the past 70 years suggests a possible change in the availability of prey between the coastal and interior regions.

Habitat Suitability Functions

The wading bird suitability index is based solely on the physical processes that concentrate aquatic prey and make them vulnerable to capture by wading birds. The index was calculated from South Florida Water Management Model version 3.5 (SFWMM) and Natural System Model version 4.5 (NSM) output for the 2-mile by 2-mile grid cells in the remnant Everglades shown in **Figure 8-2**. The index was then aggregated up to the landscape scale for each weekly time step. Two annual summary variables are used to characterize weekly patterns for a given year. Summary variables were validated against 10 years of observed wading bird nesting data for the Everglades. For each grid cell, the wading bird suitability index (SI_{WB}) has one function for water depth (SI_{depth}) and one function for water recession rate ($SI_{recession}$).

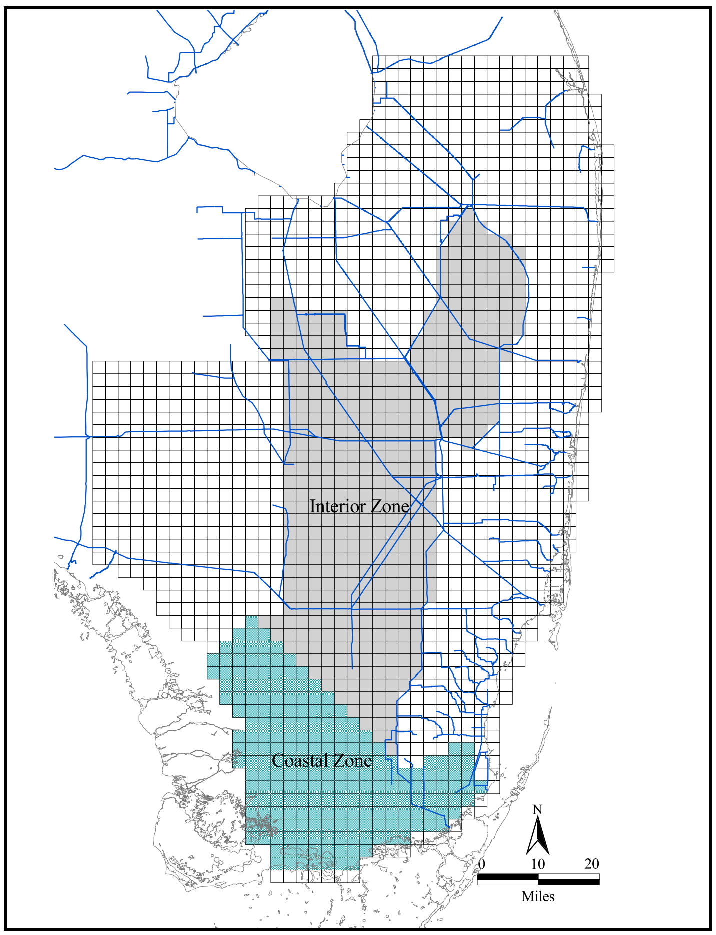


Figure 8-2. SFWMM grid cells comprising the interior and coastal zones of the remnant Everglades that are applicable for the wading bird habitat suitability index.

Water Depth

Based on both field studies and experiments (Hoffman et al. 1994, Gawlik 2002, Kushlan 1976a, 1986), it is clear that the number of wading birds at feeding sites is a quadratic function with water depth. At either very low or very high water depths bird abundance is low. The ideal water depth differs among species. For feeding sites of wood storks, white ibises, and snowy egrets, the index for a grid cell is highest when weekly average water depths (d) from November to April (the prebreeding and breeding season) are between 0.0 and 0.5 feet. The index drops to 0.0 when water depths are greater than 0.8 feet or less than 0.3 feet below marsh surface (**Figure 8-3**):

$SI_{depth} = 0.0$ for $d \leq -0.3$ feet or $d > 0.8$ feet

$SI_{depth} = (d/0.3) + 1$ for $-0.3 < d \leq 0.0$ feet

$SI_{depth} = 1.0$ for $0.0 < d \leq 0.5$ feet

$SI_{depth} = (0.8 - d)/0.3$ for $0.5 < d \leq 0.8$ feet

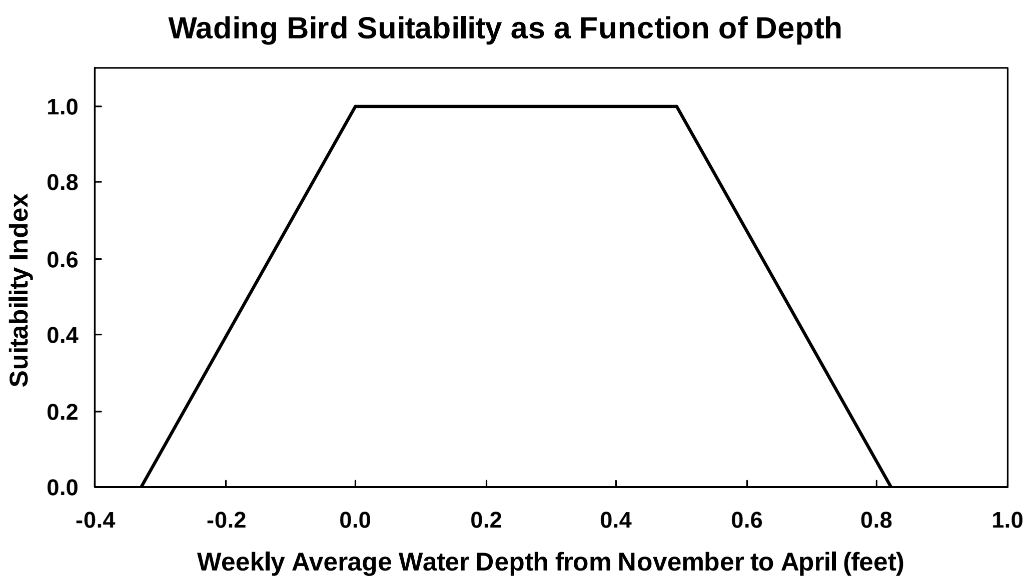


Figure 8-3. Wading bird suitability as a function of weekly average water depth from November to April.

Water Recession Rate

A rapid rate of receding water seems to produce good nesting effort (Kahl 1964, Frederick and Spalding 1994). Nest abandonment can occur when water level change is less than -0.11 feet per week or particularly when it is a positive value (Kushlan 1976b, Frederick and Collopy 1989a, 1989b). Some degree of uncertainty around the ideal recession rate was accounted for in the index by keeping the suitability of a grid cell at 1.0 when water depth change is anywhere between -0.16 and -0.05 feet per week (negative is receding water, positive is rising). There is strong evidence that reversals in water level recession causes abandonment, so the index drops sharply from 1.0 to 0.0 when water level change is between -0.05 feet per week and 0.05 feet per week. There is less evidence to substantiate the ideal recession rate of -0.11 feet per week so, accordingly, the index drops to 0.0 only when water depth change is greater than -0.6 feet per week. The average weekly change in water depth ($\Delta_{\text{ave weekly}}$) from November through April is used to calculate the water recession suitability index according to the following functions (**Figure 8-4**):

$SI_{recession} = 0.0$ for $\Delta_{\text{ave weekly}} \leq -0.6$ feet or $\Delta_{\text{ave weekly}} > 0.05$ feet

$SI_{recession} = (\Delta_{\text{ave weekly}} + 0.6)/0.44$ for $-0.6 < \Delta_{\text{ave weekly}} \leq -0.16$ feet

$SI_{recession} = 1.0$ for $-0.16 < \Delta_{\text{ave weekly}} \leq -0.05$ feet

$SI_{recession} = (0.5 - 10*\Delta_{\text{ave weekly}})$ for $-0.05 < \Delta_{\text{ave weekly}} \leq 0.05$ feet

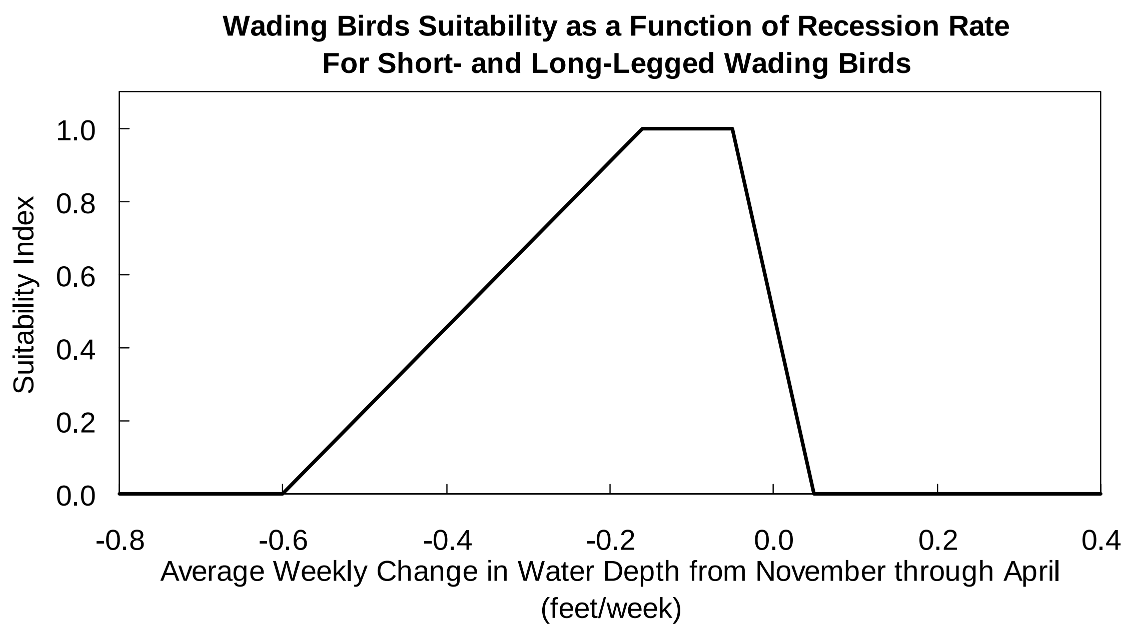


Figure 8-4. Wading bird suitability as a function of average weekly change in water depth from November through April.

Wading Bird Suitability Index

The combined wading bird suitability index for each 2-mile by 2-mile model grid cell at each weekly time step is calculated as the minimum of either recession rate or water depth scores:

$$SI_{WB} = \min(SI_{depth}, SI_{recession})$$

The scale of an individual cell, however, is not appropriate to assess habitat quality for wading birds because they follow suitable habitat as it moves across the landscape during the dry season. To have a successful nesting year, wading birds must have access to suitable habitat throughout the dry season but the location of the suitable habitat can vary across the landscape. Thus, at any one time, a highly suitable landscape will likely consist of individual cells that have not yet reached their peak suitability for the year, cells that have already passed their peak suitability, and cells that are at their highest suitability. To capture the landscape-level habitat suitability (SI_{land}), the mean suitability score for the top 23 percent of cells is calculated each week. Twenty-three percent was chosen because approximately one-quarter of the cells are occupied at any one time by feeding wading birds during a good nesting year (D. Gawlik, Florida Atlantic University, unpublished data). For the remnant Everglades, consisting of 666 model grid cells, this amounts to 150 cells having the highest values of SI_{WB}. For the coastal zone of 217 cells, the highest SI_{WB} values of 50 cells are used to compute the average. For the interior zone of 449 cells, the highest valued 100 cells are used to compute the average. Weekly SI_{land} values in each of the remnant Everglades, coastal and interior zones are used to assess the impact on wading bird habitat associated with alternative water management policies.

The suitability index described above was validated at two levels using results from the SFWMM calibration and verification runs. Individual cell values (SI_{WB}) were correlated with the observed abundance of wood storks, white ibises, and small herons on 41 monthly (November to April) systematic aerial wading bird surveys conducted from 1985 to 1995 (Bancroft and Sawicki 1995). Pearson correlation coefficients were low (wood stork $r = 0.06$, white ibis $r = 0.26$, small heron $r = 0.13$), although highly significant (all tests, $P < 0.001$) because of large sample sizes (n=34,861). Other factors besides hydrology, such as the presence of foraging flock, affect where birds forage and may contribute to the low correlation at this fine scale.

The model was validated on an annual basis by comparing the weekly landscape index (SI_{land}) with numbers of wading bird nests because numbers and distribution of nests vary with hydrology and prey availability (Kahl 1964, Frederick and Collopy 1989a, Frederick et al. 1996). The number of nests was summarized in two ways:

1. The number of nests in the water conservation areas from 1986 to 1995 (Crozier et al. 2000)

2. The number of nests in both the water conservation areas and Everglades National Park during the same period

The reason for the separate analyses is that the most appropriate scale at which to compare foraging and nesting is not clear. SI_{land} in its current form is for the entire Everglades landscape whereas most wading birds (less than 90 percent) nest in the water conservation areas. Thus, it is possible that processes in the model affect birds in one region more than birds in another.

This model validation exercise served both to validate the current model (SI_{land}) and to identify an annual summary variable(s) that was most strongly associated with nesting effort. As part of an exploratory analysis, annual summary variables were compared to determine which variable was most correlated with wading bird nesting for different species. This summary variable will be used to evaluate hydrologic simulations.

Correlations between SI_{land} and the number of nests in the water conservation areas indicated that there were two variables associated with nest numbers. The number of times SI_{land} was less than or equal to 0.5 during the nesting season was negatively correlated with numbers of nests for white ibises (r = -0.73) and small herons (r = -0.51). A nesting season was defined as March through April for white ibises and small herons and January through March for wood storks. The mean SI_{land} during the nesting season was positively correlated with nest numbers for wood stork (r = 0.59).

Correlations between SI_{land} and the numbers of nests in the entire Everglades tended to be slightly lower than for nests in the water conservation areas. This pattern gives further support for calculating SI_{land} separately for coastal and interior regions of the Everglades. The number of times SI_{land} is less than or equal to 0.5 during the nesting season was negatively correlated with numbers of nests for white ibises (r = -0.67) and small herons (r = -0.41). The mean SI_{land} during the nesting season was positively correlated with nest numbers for wood storks (r = 0.57).

The two analyses suggest that the annual summary variable that best describes that relationship for wood storks (SI_{wost}) is the average SI_{land} from January to the end of March. The most appropriate annual summary variable for white ibises and small herons (SI_{wish}) is the number of weeks during the nesting season (March through April) when SI_{land} is less than or equal to 0.5:

$$SI_{wost} = \text{mean } SI_{land}(\text{January-March})$$

$$SI_{wish} = \max(0, 1 - (\text{number of weeks } SI_{land(\text{March-April})} \leq 0.5)/6)$$

The model validation indicates that for some species, SI_{land} is related to the number of birds that attempt to nest each year but the correlations are not strong. This may have as much to do with the validation data set as it does with the habitat suitability model. Although historic wading bird nesting data are a valuable tool for assessing the state of the ecosystem, survey methodologies and effort were not standard among regions, particularly in the earlier years. Thus, as with any large-scale data set, system-wide patterns tend to be robust, whereas the large spatial variability may mask patterns at a finer scale.

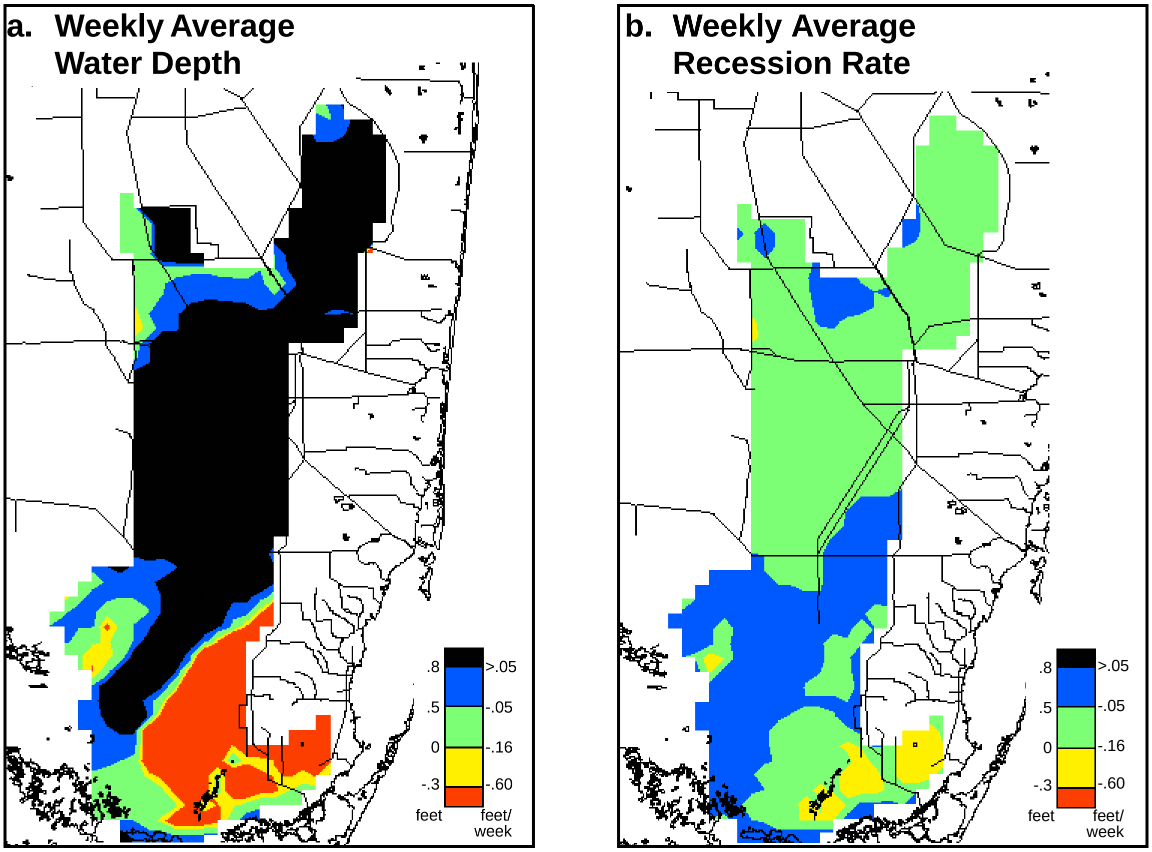
Results

Overall, wading bird suitability for white ibis and small heron (SI_{wish}) and wood stork (SI_{wost}) is not defined at particular spatial locations; rather, it is a function of adequate habitat suitability over landscapes, in this case the coastal zone, interior zone, and remnant Everglades, which combines the coastal and interior zones. Hence, there is no overall suitability map for wading birds showing spatial location of suitable habitat. However, spatial results of the component indices are used to derive the final suitability index for wading birds. Weekly water depth and water recession subindices over the dry season from November to April are used to define a combined wading bird suitability (SI_{WB}), which is then used to define landscape-level suitability. Annual suitability indices are then derived from weekly landscape-level suitability for each of the two groups of wading birds.

Water Depth and Water Recession Suitability

Before examining annual wading bird suitability time series for white ibis and small heron, and wood stork, results from the water depth and water recession suitability subindices for the current system are presented for a selected week (March 7 to 13, 1993) and then landscape-level suitability for the dry season within which that week falls are presented to explain how the annual SI_{wish} and SI_{wost} are obtained. Probability exceedance distributions of the annual wading bird suitability are used to better distinguish between wading bird suitability in the natural, current, and restored systems.

Results from water depth and water recession suitability subindices for the current system are shown for the week of March 7 to 13, 1993 in **Figures 8-5a** and **8-5b**. Water depth suitability (SI_{depth}) and water recession rate suitability ($SI_{recession}$) are produced weekly for the dry season (November to April) for each model grid cell in the remnant Everglades (**Figure 8-2**). The combined wading bird suitability index (SI_{WB}) calculated as the minimum of either SI_{depth} or $SI_{recession}$ for the same week (March 7 to 13, 1993) is shown in **Figure 8-5c**. As was described previously, to have a successful nesting year, wading birds require suitable habitat throughout the dry season but the location of the suitable habitat can very across the landscape. For the week shown in **Figure 8-5**, although the water recession rate is ideal throughout much of the water conservation areas and parts of the marl prairie, water depth is only suitable in the northern part of WCA 3A and parts of the marl prairie; hence, wading bird suitability is only high in areas coincident with both high water depth and high water recession rate suitability (i.e., in northern WCA 3A and parts of the marl prairie). Although much of the remnant Everglades has unsuitable water conditions for wading bird feeding at this particular time (**Figure 8-5c**), the landscape-level suitability (SI_{land}) is determined by the top 23 percent of SI_{WB} in the remnant Everglades, and the coastal and interior zones. **Figure 8-6** shows the time series of SI_{land} for the dry season of 1992-1993 for the same three areas. Week 18 in **Figure 8-6** represents the values of SI_{land} that correspond to the water depth, recession rate, and SI_{WB} shown in **Figure 8-5**. Wood stork suitability for each year is determined as the mean of the SI_{land} values from January to March. For 1993, in the current system, SI_{wost} is the mean of the SI_{land} values from week 9 to week 20 in **Figure 8-6**. White ibis and other small heron



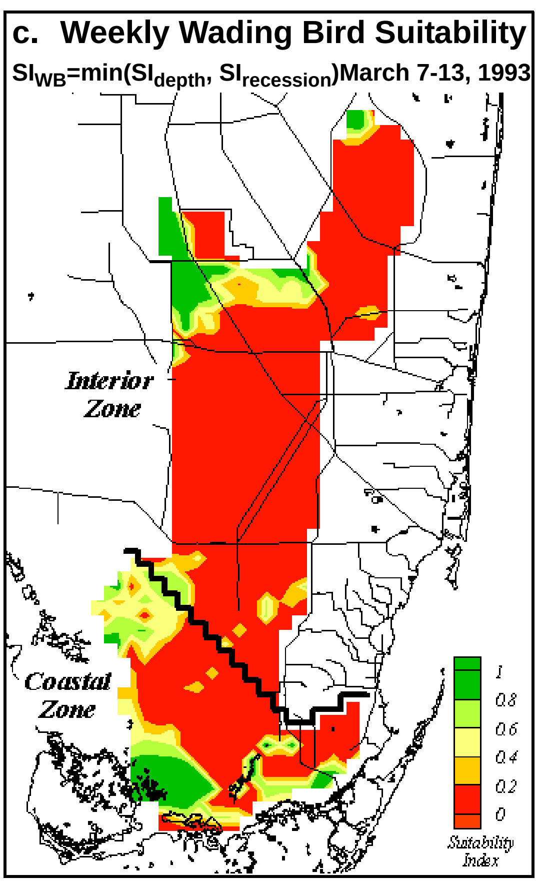


Figure 8-5. a. Average water depth, b. recession rate, and c. wading bird suitability for the week of March 7 to 13, 1993, as simulated for the current system.

suitability SI_{wish} is determined as a function of the number of weeks between March and April (week 17 to 25) when SI_{land} is less than 0.5.

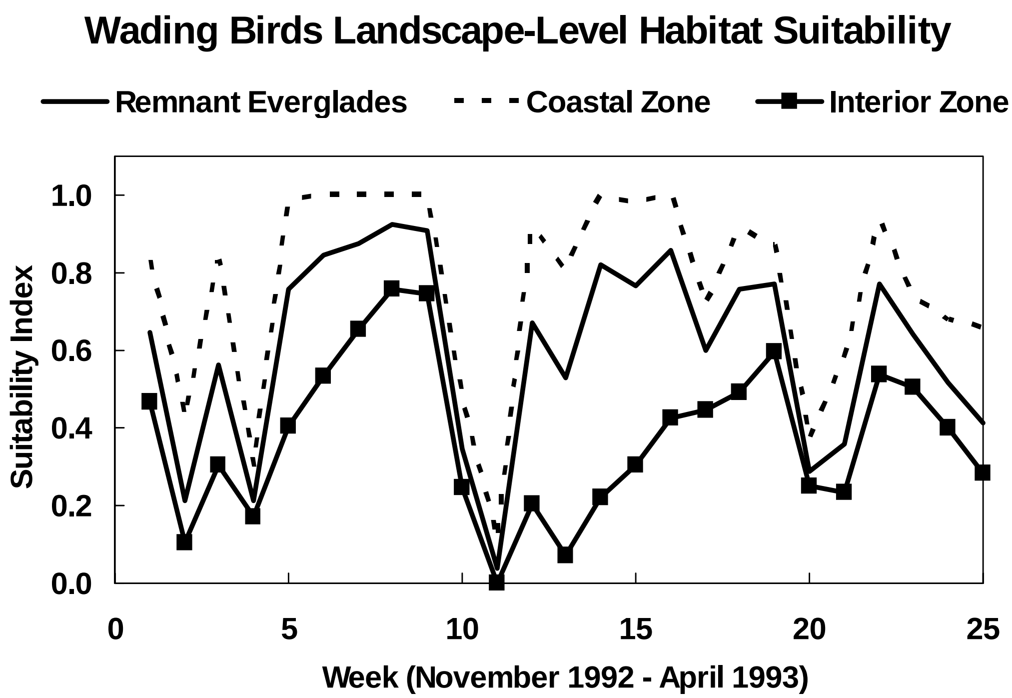


Figure 8-6. Landscape-level habitat suitability for wading birds for the period from November 1992 to April 1993 as simulated for the current system for the a. coastal zone, b. interior zone, and c. remnant Everglades.

White Ibis and Small Heron

For white ibis and small heron in the coastal zone, suitability is generally high (> 0.6) for the natural system (**Figure 8-7a**). Current system suitability is lower than that of the natural system and fluctuates more, with suitability below a value of 0.6 in 6 years and as low as 0.0 in 2 years. **Figure 8-8a** indicates approximately 80 percent probability that SI_{wish} is higher than 0.6 in the current system. The restored system suitability for white ibis and small heron is very similar to that of the natural system with an 80 percent probability of SI_{wish} being higher than 0.8 (**Figure 8-8a**).

In the interior zone, it is not as easy to distinguish between natural, current, and restored system suitability for white ibis and small heron. Suitability fluctuates more than in the coastal zone and is as low as 0.0 in several years for all three simulations (**Figure 8-7b**). Probabilities of attaining particular suitability thresholds are similar (**Figure 8-8b**) with a 70 percent probability that SI_{wish} is higher than 0.6 in the current system and approximately 80 percent probability that SI_{wish} is higher than 0.6 in the natural and restored system simulations.

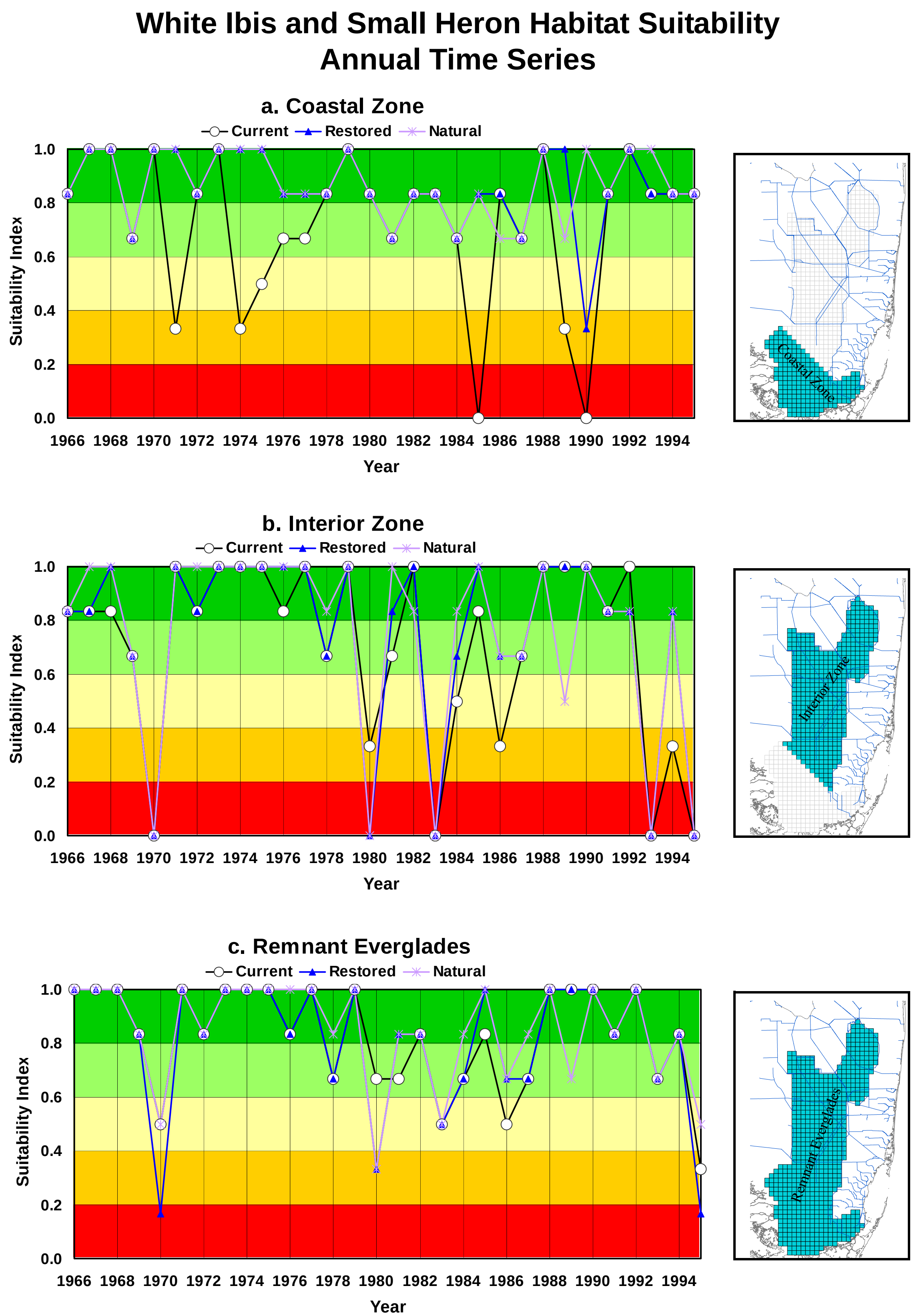


Figure 8-7. Annual time series of white ibis and small heron suitability for the a. coastal zone, b. interior zone, and c. remnant Everglades.

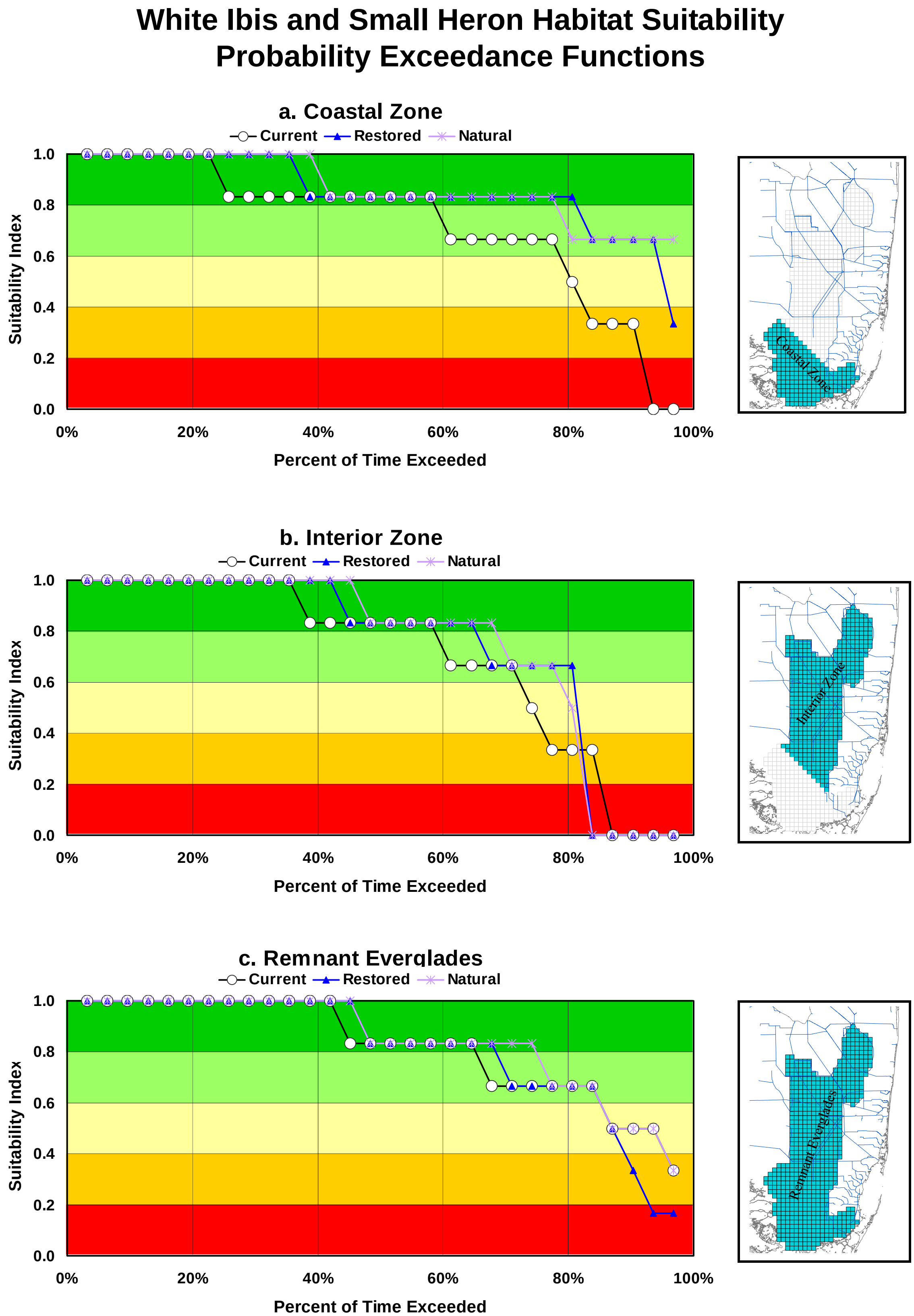


Figure 8-8. Probability exceedance functions of white ibis and small heron suitability for the a. coastal zone, b. interior zone, and c. remnant Everglades.

For the remnant Everglades, which combines the coastal and interior zones, differences between SI_{wish} suitability for the three simulations are relatively small (**Figures 8-7c** and **8-8c**). Suitability in the restored system fluctuates slightly more than in the natural and current systems dropping below a value of 0.4 in 3 years (probability of 10 percent) while in the natural and current system SI_{wish} drops below 0.4 in one year (probability of 5 percent).

Wood Stork

For wood storks, there is almost no difference between natural, current, and restored system habitat suitability in the coastal zone (**Figures 8-9a** and **8-10a**). Average suitability for wood stork, SI_{wost} is above 0.8 with relatively little annual fluctuation around this value. Wood stork habitat quality may decrease in the interior of the system with restoration, however, habitat quality should increase in the coastal zone (see **Chapter 10**). If the increased habitat quality in the coastal zone leads to increased wood stork nesting, it will fulfill one of the restoration goals and produce a pattern that was characteristic of the natural system.

In the interior zone, the year-to-year fluctuation of wood stork suitability increases considerably with SI_{wost} values ranging from 0.1 to almost 1.0 (**Figure 8-9b)**. Differences between the natural, current, and restored system simulations are still small although some distinction can be made. Restored system suitability tends to be slightly lower than that of the natural system which is in turn slightly lower than that of the current system. There is a 60 percent probability that SI_{wost} is higher than 0.6 in the restored system compared to a 70 percent probability that SI_{wost} is higher than 0.6 in the natural and current systems (**Figure 8-10b**).

In the remnant Everglades, annual SI_{wost} values fluctuate from 0.4 to almost 1.0 with very small differences between the natural, current, and restored system simulations (**Figure 8-9c**). There is slightly more than 80 percent probability that SI_{wost} is higher than 0.6 in the natural and restored systems compared to more than 90 percent probability that SI_{wost} is higher than 0.6 in the current system (**Figure 8-10c**).

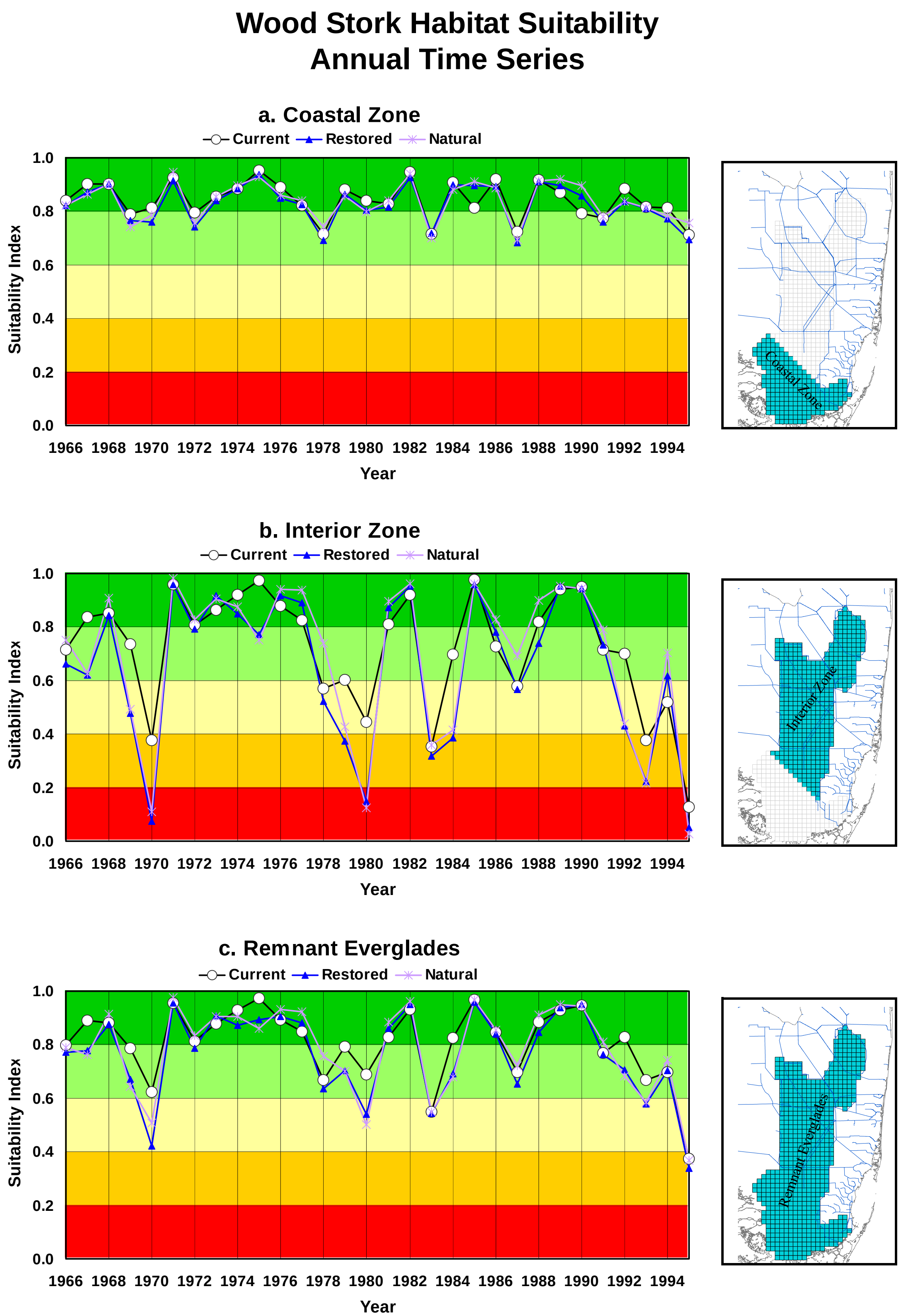


Figure 8-9. Annual time series of wood stork suitability for the a. coastal zone, b. interior zone, and c. remnant Everglades.

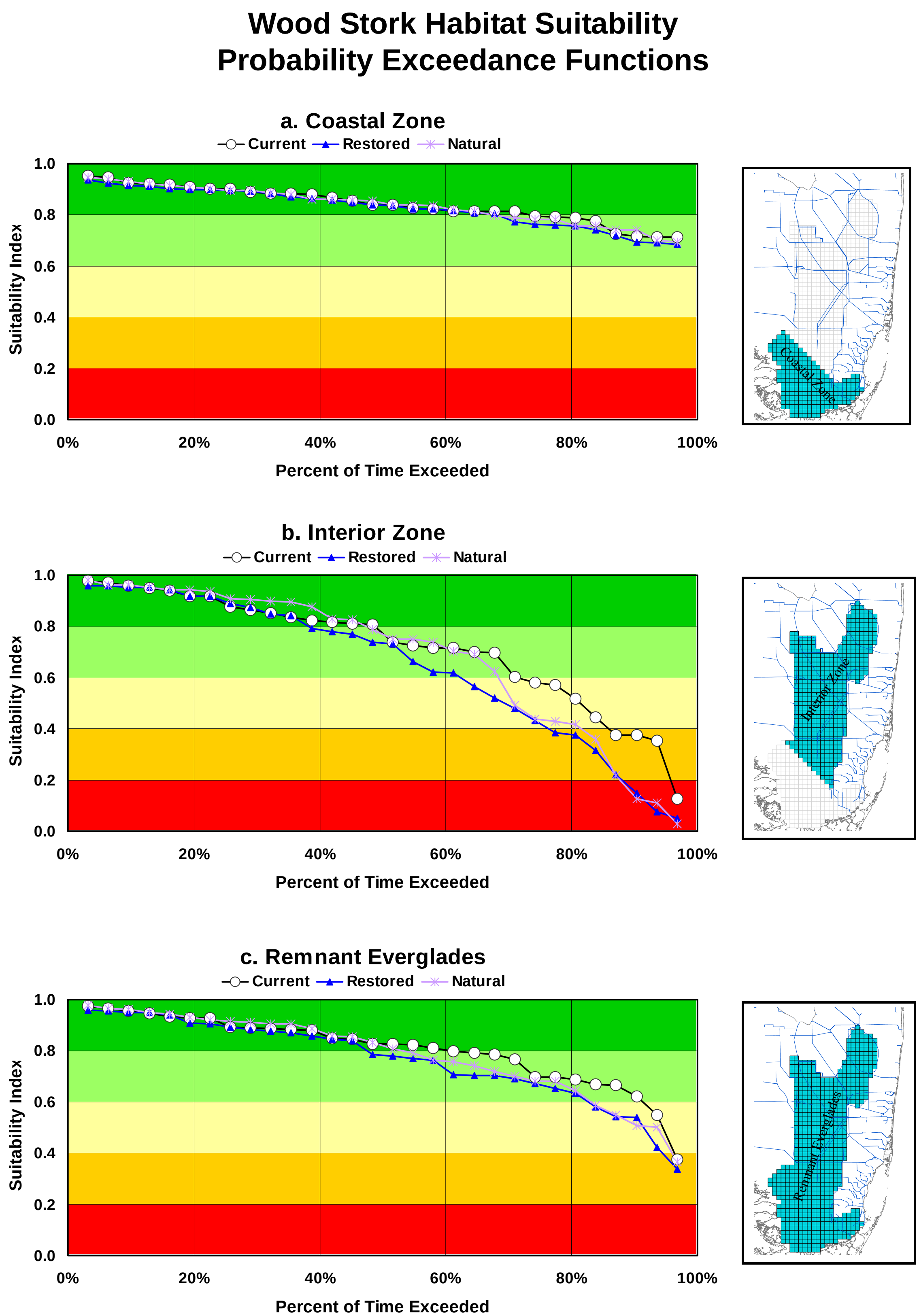


Figure 8-10. Probability exceedance functions of wood stork suitability for the a. coastal zone, b. interior zone, and c. remnant Everglades.

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CHAPTER 9

Comparisons to Evaluate Water Management Strategies

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Introduction

In this section, tools (graphics and tables) that can be used to compare habitat suitability indices in the evaluation of water management alternatives are demonstrated. In the results section of the preceding chapters (3 though 8), the natural, current, and restored systems as simulated using the Natural System Model version 4.5 and the South Florida Water Management Model version 3.5 were compared for each individual suitability index. This chapter discusses how suitability indices can be used to show trade-offs between ecological indicators in comparing alternative water management strategies. These types of comparison can be very useful in highlighting areas and instances where a water management action that is designed to achieve some degree of restoration (improving the quantity, quality, timing and distribution of water) may improve some ecological indicators while impacting others. Comparison between indices allows for review of water management strategies and also adds to understanding the relationship between habitat suitability indicators allowing for their refinement as appropriate.

Long-term habitat suitability, which is a function of hydrologic conditions over the model simulation period of record, was presented for the landscape-scale suitability functions: ridge and slough landscape, periphyton, and tree islands. Time-varying indices for fish and alligators were developed and averaged over the period of simulation to produce overall spatially-variable suitability. For tree islands, two habitat suitability indices were developed that proved to be most useful: tree island species richness index, which is a period-of-record spatially-varied value, and tree island suitability index, which is a time varying index. For wading birds, time varying indices were produced for each of three zones: the remnant Everglades and the interior and coastal zones of the remnant Everglades.

Overall spatial comparisons between indices are presented first (i.e., comparison of average or long-term suitability for each location or model grid cell), followed by temporal comparisons between indices for a particular spatial location (e.g., a sample indicator region as in **Figure 9-2**). Then a way of comparing temporally-averaged and period-of-record indices by spatial location is presented. Finally, two scenarios are used

1. South Florida Water Management District

(with the same sample indicator region) to show how suitability indices can be used to evaluate the effect on habitat suitability of different water management strategies.

Spatial Comparisons

Comparison of the long-term or period-of-simulation average suitability indices for the ridge and slough landscape, tree island species richness, periphyton, fish, and alligators is presented in **Figure 9-1** for the simulated restored system. The graphic for each individual habitat was presented previously when comparisons between alternatives were made for each index, however examination of suitability in space across indices for the same alternative allows for interesting comparisons of suitability patterns between indices or habitats.

Examination of **Figure 9-1** reveals several key areas of trade-offs between habitat suitability as follows:

- Shark River Slough appears highly suitable for fish and alligators, is relatively less suitable for ridge and slough and tree islands, and has poor suitability for periphyton.
- The marl prairie areas (see Ochopee Marl Marsh and Rockland Marl Marsh on **Figure 3-1**) on the edges of Shark River Slough are well suited to periphyton production but less suitable for alligators. They fall outside the domain of the ridge and slough, tree island and fish suitability indices.
- Water Conservation Area (WCA) 3B has low suitability for the ridge and slough landscape and periphyton production, relatively better suitability for alligators and tree islands, and high suitability for fish.
- The area of highest ridge and slough suitability is in WCA 3A northwest of the L-67 canal and south of Alligator Alley. This area is also highly suitable for fish and periphyton, however, it is less suitable for alligators and hydrology in this area will likely impact tree island species richness particularly north of the Miami Canal.
- WCA 2A is highly suitable for periphyton and fish while it has moderate suitability for alligators and low suitability for the ridge and slough landscape and tree islands.
- The Arthur R. Marshall Loxahatchee National Wildlife Refuge (LNWR) has high fish and tree island species richness suitability (except in the south), moderate suitability for alligators, and poor suitability for periphyton and the ridge and slough landscape.

Similar graphics and analysis could be produced for the natural and current system. The point is, that by comparing spatial habitat suitability between indices, areas can be identified where the hydrology of a particular water management strategy (e.g., the current or restored system) makes habitat more suitable for one habitat while making it

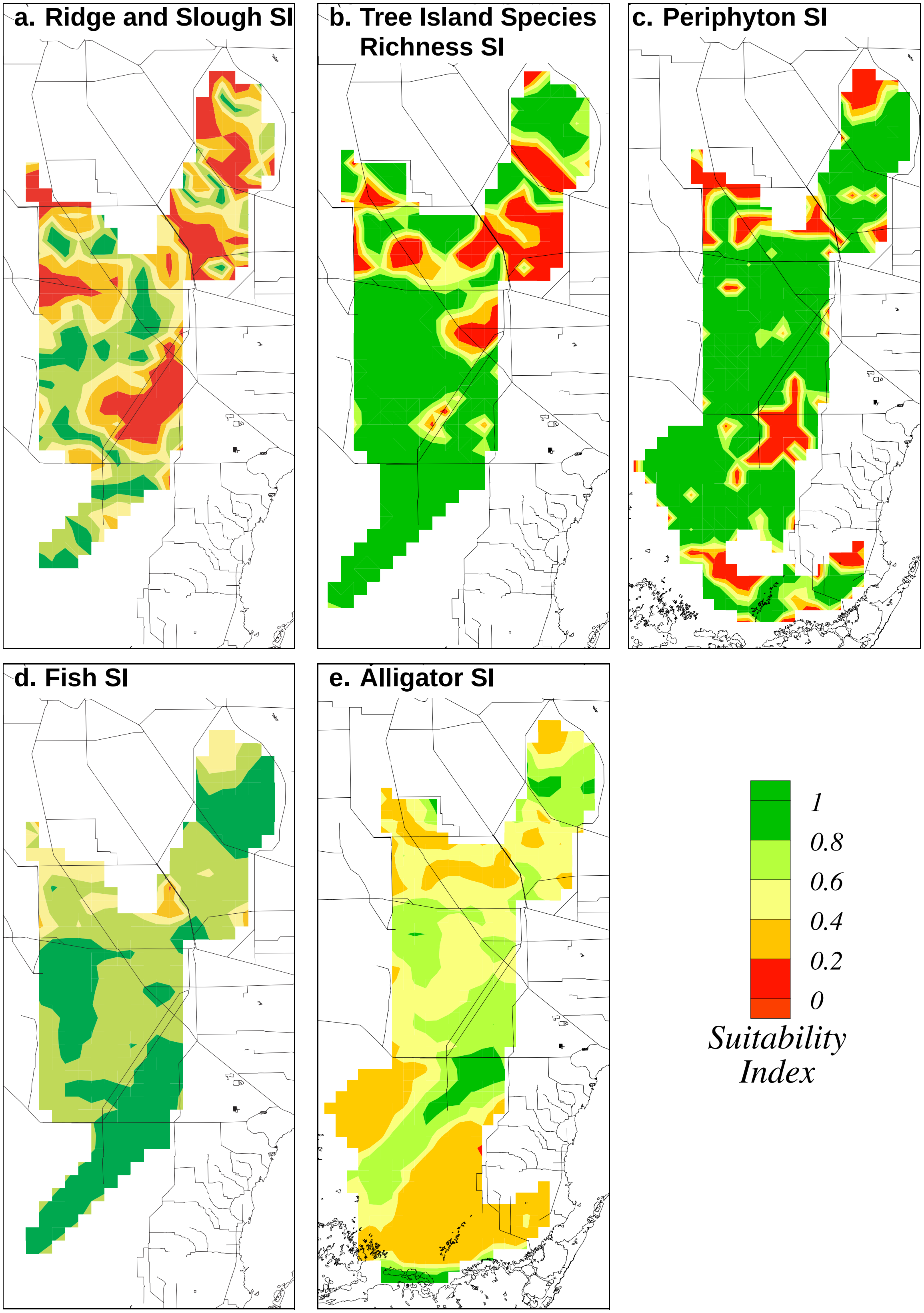

Figure 9-1. Comparison of simulated restored system habitat suitability indices (SIs) for a. ridge and slough landscape, b. tree island species richness, c. periphyton, d. fish, and e. alligators.

less suitable for another habitat. When examined in this way, spatial comparisons between habitat suitability indices can provide very useful information.

The overall spatial average suitability index could have been determined for each habitat, but this provides very little additional information. Overall average index values would likely be very similar and would mask the different, and sometimes contrasting, levels of suitability in different areas. An overall average would not tell us, for example, that for the restored system, the simulated hydrology results in poor suitability for ridge and slough in the same area (LNWR) that there is high suitability for tree islands.

The usefulness of habitat suitability indices is that they can identify areas where trade-offs may occur. In some cases these trade-offs may be valid. For example, restoration goals might seek to maintain tree island species richness in LNWR at the expense of not restoring the ridge and slough landscape in this area. However, in other cases, the indices may point to areas of concern that require further investigation using more complex individual species models or revisiting features of the particular management strategy that cause the trade-off to occur.

Temporal Comparisons

Temporal comparisons can be made at specific locations (normally indicator regions) to give an indication of when trade-offs between habitat suitability occur due to changing hydrologic conditions. Shark River Slough Indicator Region 129 (**Figure 9-2**) is used as an sample indicator region for temporal comparisons. In **Figure 9-3**, fish, alligator, and the tree island habitat suitability (not tree island species richness) are compared for the Shark River Slough indicator region for the natural system simulation. Fish suitability in this indicator region is fairly insensitive to hydrologic change; it remains above a value of 0.8 for most years and has a mean value of 0.92 for the period of simulation (1965 to 1995). Alligator suitability fluctuates more with hydrologic change; it ranges from values below 0.4 to values close to 1.0 and has a mean value of 0.76 for the period of simulation. Tree island suitability is very sensitive to hydrologic change; it ranges from 0.0 to 1.0 with a mean value of 0.19 for the period of simulation. The temporal pattern of suitability for fish and alligators is fairly consistent, while there is a trade-off or inverse relationship between alligator and tree island suitability in this indicator region. In relatively dry years, particularly 1981 and 1990, tree island suitability is high because the risk of flooding is reduced. In these same years, shallower depths reduce alligator suitability. A deviation from this pattern is 1978 when tree island suitability is high while alligator suitability also remains high. In this case, the timing of dry out that reduced the risk of flooding for tree islands was such that it did not impact alligator suitability.

Suitability indices can be combined for a particular alternative at a specific location (normally an indicator region). The fish, alligator, and tree island suitability indices, presented in **Figure 9-3** for the natural system were combined in **Figure 9-4** to produce a mean combined suitability index for the natural system for the Shark River Slough indicator region. A similar process was used to produce combined suitability

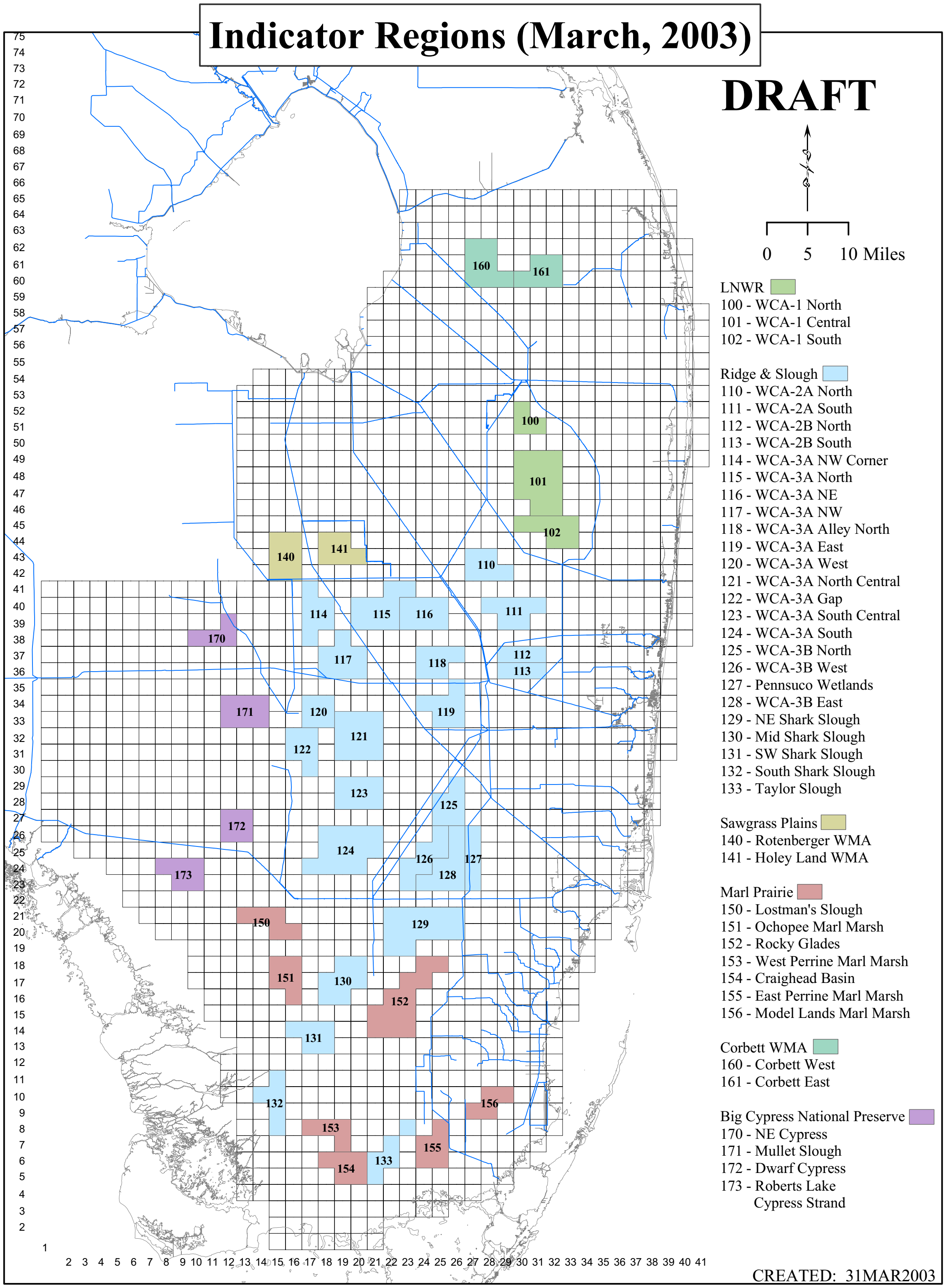

Figure 9-2. Indicator region map, color-coded by landscape type.

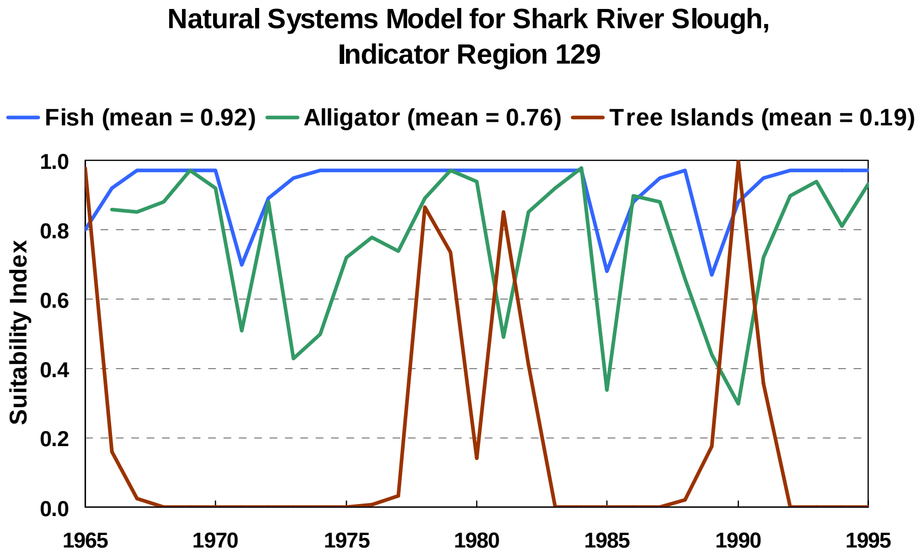

Figure 9-3. Comparison of fish, alligator and tree island habitat suitability in Shark River Slough Indicator Region 129 for the natural system.

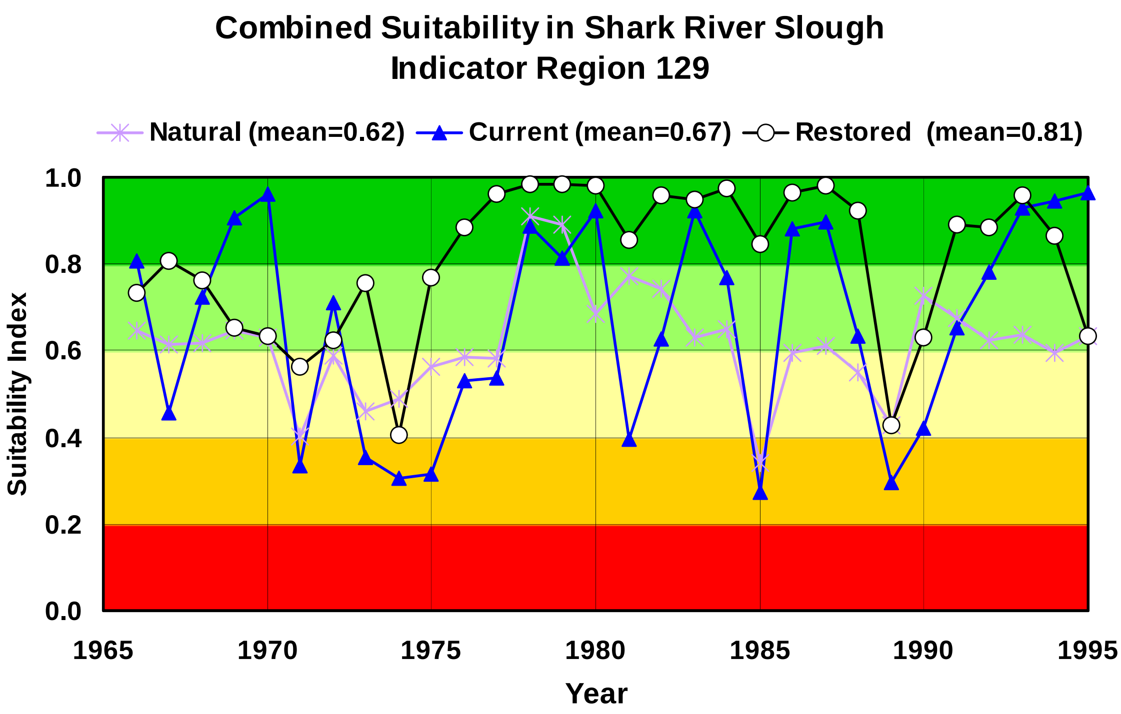

Figure 9-4. Comparison of combined (fish + alligator + tree island) suitability indices for the natural, current, and restored systems in Shark River Slough Indicator Region 129.

indices for the current, and restored systems. Combination of multiple or selected indices could involve any desired weighting scheme to reflect the relative importance of the habitat or objectives of the project. In this case, an equal weighting was given to each of the indices. Comparison and interpretation of combined habitat suitability indices is not as clear as comparison and interpretation of individual indices. Combination results in a degree of loss of information. In this case, it can be said that the restored system has higher combined habitat suitability for most years and an overall higher mean suitability (0.81) than the current system (mean = 0.67) and the natural system (mean = 0.62). In some instances, combination of indices can provide useful information to answer specific questions.

Temporal comparisons for the entire landscape are not discussed because the averaging of a range of suitability from different parts of the landscape into a single number would render these comparisons relatively meaningless.

Average Temporal and Spatial Comparison

Averaging temporally-variable suitability indices (e.g., tree island suitability index, small fish, and alligator in **Figure 2-1**) for specific indicator regions over the period of record is appropriate and provides meaningful information. In the example given in **Figure 9-3**, the Shark Slough indicator region is better suited to fish habitat (mean = 0.92) than alligators (mean = 0.76) and has low suitability for tree islands (mean = 0.19).

Temporally-averaged suitability indices (e.g., tree island species richness index, ridge and slough, and periphyton in **Figure 2-1**) for indicator regions can be compared with indices averaged over the period of record for the same indicator regions, permitting wider comparison of habitat suitability by indicator region. Furthermore, mean or period-of-record suitability values for each indicator region (**Figure 9-2**) can be combined into landscape-type average suitability values. An example of this type of comparison is shown in **Table 9-1** for the current (95BSR) and restored (D13R) systems. Values in **Table 9-1** are used to depict the type of comparisons that could be made with this table. Suitability values could be compared between alternatives and between habitats horizontally across the table for each indicator region. The table uses period-of-record values for the ridge and slough landscape, tree island species richness, and periphyton, while using average values for the simulation period (equal to the period of record) for fish and alligators.

Habitat suitability between indicator regions could be compared vertically down the columns of **Table 9-1**. The shaded rows indicate landscape-type average suitability, i.e., the average suitability for a particular landscape. This allows for comparisons of habitat suitability between alternatives within a landscape type and also comparison of habitat suitability between landscape types.

Table 9-1. Comparison of habitat suitability indices by indicator region and for landscape types comprising several indicator regions as defined in **Figure 9-2**. Suitability increases with increasing index value from 0 to 1.

Indicator Number and Name		# Cells	Ridge and Slough		Tree Islands		Periphyton		Fish		Alligators	
			95BSR	D13R	95BSR	D13R	95BSR	D13R	95BSR	D13R	95BSR	D13R
100	WCA 1 North	3	0.10	0.04	0.67	0.67	0.03	0.03	0.50	0.49	0.25	0.25
101	WCA 1 Central	11	0.25	0.26	0.98	1.00	0.77	0.72	0.80	0.78	0.66	0.64
102	WCA 1 South	6	0.19	0.27	0.44	0.50	1.00	0.99	0.92	0.89	0.78	0.76
LNWR Indicator Region Average[a]			0.21	0.23	0.77	0.80	0.73	0.70	0.79	0.77	0.63	0.62
110	WCA 2A North	5	0.24	0.31	0.39	0.61	0.82	0.98	0.65	0.70	0.45	0.49
111	WCA 2A South	6	0.51	0.37	0.90	0.59	1.00	1.00	0.72	0.72	0.48	0.52
112	WCA 2B North	3	0.48	0.68	0.39	0.38	0.95	0.68	0.71	0.67	0.58	0.49
113	WCA 2B South	3	0.19	0.22	0.00	0.00	1.00	0.88	0.75	0.73	0.60	0.58
114	WCA 3A Northwest Corner	6	0.40	0.53	0.00	1.00	0.04	0.92	0.52	0.71	0.22	0.51
115	WCA 3A North	5	0.31	0.54	0.00	0.40	0.15	0.61	0.54	0.62	0.27	0.40
116	WCA 3A Northeast	5	NA[b]	NA	0.12	0.88	NA	NA	NA	NA	0.26	0.38
117	WCA 3A Northwest	7	0.52	0.46	0.53	0.69	0.65	0.67	0.64	0.71	0.42	0.50
118	WCA 3A Alley North	5	0.57	0.73	0.74	0.81	1.00	0.93	0.78	0.70	0.66	0.48
119	WCA 3A East	6	0.42	0.87	0.00	0.78	0.91	1.00	0.90	0.78	0.71	0.59
120	WCA 3A West	4	0.60	0.52	0.57	1.00	1.00	0.74	0.67	0.86	0.46	0.76
121	WCA 3A North Central	9	0.74	0.64	1.00	0.94	1.00	0.90	0.75	0.82	0.55	0.63
122	WCA 3A Gap	5	0.54	0.54	1.00	0.83	0.38	0.96	0.63	0.80	0.38	0.59
123	WCA 3A South Central	6	0.65	0.71	1.00	0.97	1.00	0.89	0.79	0.77	0.64	0.54
124	WCA 3A South	12	0.56	0.76	0.08	1.00	0.47	1.00	0.89	0.79	0.72	0.59
125	WCA 3B North	5	0.56	0.23	0.13	0.08	1.00	1.00	0.80	0.81	0.69	0.67
126	WCA 3B West	6	0.30	0.42	0.97	1.00	1.00	0.61	0.81	0.91	0.68	0.76
127	Pennsuco Wetlands	4	0.00	0.09	0.05	0.80	0.01	0.82	0.56	0.78	0.48	0.68
128	WCA 3B East	7	0.16	0.42	0.66	0.93	0.96	0.68	0.71	0.90	0.60	0.78
129	Northeast Shark River Slough	12	0.12	0.64	0.69	0.88	0.83	0.23	0.70	0.93	0.53	0.83
130	Mid-Shark River Slough	7	0.74	0.77	1.00	0.99	1.00	0.51	0.75	0.92	0.57	0.80
131	Southwest Shark River Slough	5	NA	NA	0.26	1.00	0.93	1.00	0.66	0.81	0.46	0.68
132	South Shark River Slough	5	NA	NA	NA	NA	NA	NA	NA	NA	0.44	0.62
133	Taylor Slough	5	NA	NA	NA	NA	1.00	0.99	NA	NA	0.27	0.26
Ridge and Slough Indicator Region Average			0.44	0.55	0.51	0.80	0.77	0.79	0.72	0.80	0.52	0.61

a. Landscape-average habitat suitability index is calculated by weighting the habitat suitability index for each indicator region within the landscape type by the number of cells in the indicator region. Only applicable indicator regions (without NA) are averaged to obtain landscape-average habitat suitability index.

b. NA means the indicator region is not completely within the applicable grid for the habitat suitability index.

Scenario Comparisons

Habitat suitability indices are useful when evaluating different management scenarios to see how a particular scenario might affect ecology in particular areas. The preceding chapters (3 through 8), already have considerable discussion of differences between the natural, current, and restored system for each suitability index. Suitability indices can also be used to look at the specific effect of a management scenario on a particular performance measure. Two scenarios based in the restored system were simulated to illustrate this approach. In scenario 1, all aquifer storage and recovery features (with a pumping capacity of 5,000 acre-feet per day) were removed from the restored system. These features were located predominantly around Lake Okeechobee, in the Caloosahatchee basin, and in the Lower East Coast developed area. In scenario 2, storage capacity in the in-ground storage (280,000 acre-feet) north and south of Miami Canal in the Lower East Coast developed area was removed from the restored system. Following the example above, the effect of these two scenarios on Shark River Slough Indicator Region 129 was investigated for alligator habitat suitability.

A probability exceedance function for alligator suitability, shown in **Figure 9-5** indicates that for this particular region, the removal of aquifer storage and recovery features has negligible effect on alligator suitability. At the same time, a considerable reduction in alligator suitability is caused by removing the in-ground storage areas. The probability of alligator suitability in Indicator Region 129 exceeding a value of 0.8 is reduced from around 75 percent to around 40 percent when in-ground storage is removed. The mean (50 percent probability) alligator suitability is reduced from a value of 0.81 for the restored system to a value of 0.64 with the in-ground storage areas removed.

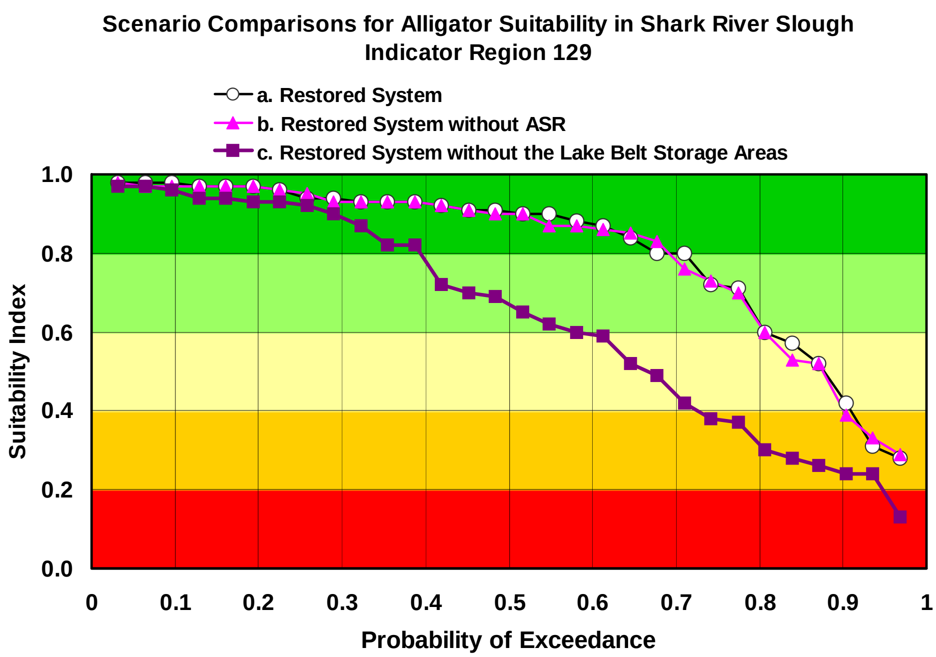

Figure 9-5. Probability exceedance function for alligator suitability in Shark River Slough Indicator Region 129, for the a. restored system, b. restored system without aquifer storage and recovery (ASR), and c. restored system without the Lake Belt storage areas.

Summary

Spatial comparisons can highlight areas where trade-offs between habitat suitability functions occur in different simulated water management alternatives. These trade-offs can be further investigated using more complex models if necessary. Temporal comparisons provide a means of seeing the year-to-year trade-offs between habitat suitability and the sensitivity of individual suitability functions to hydrologic change. Temporal averaging for specific locations (indicator regions) or even landscape types can provide useful information for comparison purposes and permits comparison between period-of-record suitability indices and temporally-averaged (over the simulation period) suitability indices. Comparison of habitat suitability at particular locations for different water management strategies or scenarios can reveal information about the effects of these strategies at those locations. Indicator regions can be used to highlight particular management strategies that cause habitat suitability impacts and the location (indicator region) in which the impacts occur. This allows for refinement of the management features causing habitat suitability impacts, further investigation, or refinement of the suitability indices if necessary.

CHAPTER 10

Ecological Synthesis

Steven M. Davis[1]

Introduction

The habitat suitability indices, although simplistic, reflect current available information and the best thinking of the teams of experts who created them. For the purpose of this synthesis, the models are considered to provide trends and degrees of ecological response that allow comparison of predrainage, current, and restored hydrologic conditions. In that context, the models may provide insights about how the selected landscape features and faunal groupings have changed with the drainage and compartmentalization of the Everglades, and how and to what degree the restoration of more natural hydropatterns will result in the restoration of desired ecological trends. A synthesis that examines patterns or themes common to more than one model can reveal relationships that are not apparent from an examination of each habitat suitability index model individually.

Ridge and Slough and Tree Island Sustainability

The ridge and slough habitat suitability index suggests that conditions for ridge and slough development were strongest in the natural system in the deep-water, prolonged-hydroperiod flow corridor of Shark River Slough. Conditions would have been less favorable for ridge and slough development in the more expansive peatlands to the north, although ridge and slough patterns are also evident there. By comparison, conditions for ridge and slough development in the current system are diminished in Shark River Slough and have shifted to central Water Conservation Area (WCA) 3A. Comprehensive Everglades Restoration Plan (CERP) water management policies seem to restore conditions favorable for ridge and slough development in Shark River Slough, while maintaining those in central WCA 3A.

Conditions favorable for ridge and slough development also appear to sustain tree islands. Both of the tree island habitat suitability index models, the species richness suitability index and the tree island suitability index, show similar broad patterns of habitat suitability for tree islands. Patterns common to both models indicate that conditions most favorable for tree islands, under both natural and restored conditions, occur in Shark River Slough extending northward into WCA 3B, in central WCA 3A, and

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in the central portion of the Arthur R. Marshall Loxahatchee National Wildlife Refuge (LNWR). Under current conditions, tree island habitat tends to be diminished both in quality and spatial extent in each of these areas in both models. Comparison of the ridge and slough and tree island habitat suitability indices shows a general overlay of areas of high tree island habitat suitability with areas of high ridge and slough habitat suitability.

Shifts in Habitat Suitability for Fauna between Shark River Slough and the Water Conservation Areas

Both the fish and alligator habitat suitability indices indicate a shift in high-suitability habitats from Shark River Slough and the oligohaline zone of the southern Everglades predrainage, to the artificially impounded areas of the water conservation areas under current conditions. Highly suitable habitat subsequently returns to the southern Everglades upon hydrologic restoration. The habitat shifts in fish and alligators followed shifts in conditions that were favorable for sustaining ridge and slough landscape patterns.

The fish habitat suitability index indicates that habitats in the natural system were close to ideal for the build-up of marsh fish densities throughout Shark River Slough. This was due to prolonged hydroperiod durations in the slough. The altered distribution of hydroperiod durations in the current system moves the habitat supporting highest densities of marsh fishes northward to artificially pooled areas of WCA 3 and LNWR. Conversely, the overdrained northern areas of WCA 3 and LNWR in the current system support reduced fish densities compared to the natural system. The return of prolonged hydroperiod durations to Shark River Slough in the restored system also returns high fish densities to the slough extending upstream throughout much of WCA 3B. The restored system also provides habitat supporting high fish densities in west-central WCA 3A and in the southern half of LNWR in areas of lesser fish habitat suitability under natural conditions.

The alligator habitat suitability index identifies Shark River Slough as the habitat most suitable for alligators under natural conditions. Under current conditions, alligator habitat has deteriorated in Shark River Slough, and has been replaced by areas of higher suitability in WCA 3 and LNWR. High-suitability alligator habitat returns to Shark River Slough in the restored system, while it remains in large tracts of central and southeastern WCA 3A, WCA 3B, and LNWR. However, increases in the alligator populations expected in edge habitat such as the marl marshes are not reflected in these alligator habitat suitability indices. The scale (2-miles by 2-miles) is too course to capture microtopographic variation such as alligator holes, animal tracks, and tree islands. Further, since most components of the index were developed using data from Shark River Slough, the application of the index throughout the Everglades system must be for comparisons of relative effects of alternatives only.

Production and Concentration of Marsh Fishes as Factors Controlling Wading Bird Reproduction

The decline in wading bird nesting in the Everglades is attributed both to altered patterns of production of marsh fishes and other prey organisms during wet periods, and to altered patterns of concentration and availability of those prey organisms to wading birds as water levels recede. The fish habitat suitability index indicates habitat suitability for the build-up of marsh fish population densities during wet periods across the ridge and slough landscape based on the distribution of hydroperiod durations. The wading bird habitat suitability index indicates habitat suitability for the concentration and availability of those fish populations to wading birds based on dry season water depths and water recession rates. Comparing the outputs from the two models provides insights regarding the respective contributions of forage production and concentration in the decline and the restoration of wading bird nesting in the Everglades.

Most of the decline in wading bird nesting in the Everglades has involved abandonment of traditional coastal and tributary colony sites along the mangrove estuaries in the southern part of the system. Nesting colonies now form mostly in the water conservation areas, where colonies often fail to produce fledging young.

The shift in location of wading bird nesting from the southern Everglades to the water conservation areas closely corresponds to the fish habitat suitability index output indicating a shift in location of habitat supporting high fish population densities from Shark River Slough to artificially pooled areas of WCA 3 and LNWR. The return of habitat supporting high fish densities to Shark River Slough in the restored system should contribute to the return of wading bird nesting to the mangrove fringe of the southern Everglades.

The wading bird habitat suitability index indicates that water depths and recession rates in the coastal zone of the southern Everglades provide a stable, high quality foraging habitat for wood storks under natural, current, and restored scenarios. This stability and high quality of foraging conditions, in combination with the decline in habitat suitability for the production of high fish densities, suggests that wood stork nesting in the southern Everglades may be limited by the production rather than the concentration of suitable prey organisms. This argument is strengthened by the size distribution of the fishes upon which the storks feed. Wood storks eat fishes greater than 10 centimeters (4 inches) in length, consisting largely of centrarchids (sunfishes), which require prolonged hydroperiod durations for growth to that size. Since hydroperiod duration is the controlling variable in the fish habitat suitability index, it makes sense that the decline and projected recovery of wood stork nesting in the southern Everglades corresponds closely to outputs from the fish habitat suitability index.

The wading bird habitat suitability index indicates that water depths and recession rates in the coastal zone of the southern Everglades also provide a stable, high quality foraging habitat for white ibis and small herons under natural and restored scenarios. However, white ibis and small herons differ from wood storks in that their foraging habitat

in the coastal zone is degraded under current conditions. The reduced stability and quality of foraging conditions, in combination with the decline in habitat suitability for the production of high fish densities, suggest that white ibis and small heron nesting in the southern Everglades currently may be limited by both the production and the concentration of suitable prey organisms.

The fish habitat suitability index suggests that wood storks, white ibis, and small herons may be drawn to the water conservation areas under current conditions by the shift in distribution of long-hydroperiod habitats supporting high fish densities. However, the wading bird habitat suitability index suggests that water depths and recession rates there provide lower quality foraging habitat in comparison to the coastal zone of the southern Everglades under all scenarios. Thus, the quality of foraging habitat, rather than the production of an adequate prey base, would appear to limit wood stork, white ibis, and small heron nesting success in the water conservation areas.

Trade-off between Periphyton Community and Other Variables in the Ridge and Slough Landscape

The proliferation of a floating mat periphyton community in Shark River Slough under current conditions appears to be an artifact of drainage. The periphyton habitat suitability index indicates that this community would disappear from most of northeastern and mid-Shark River Slough under natural and restored patterns of hydroperiod duration and depth. The same trend is seen in the estuarine interface of southern Shark River Slough. Maintaining floating mat communities in Shark River Slough under reduced hydroperiod and depth patterns would represent a trade-off between managing for floating periphyton mats versus the other ecological attributes that would benefit from hydrologic restoration. The periphyton habitat suitability index is based on our current understanding of periphyton ecology and distribution in the Everglades, more so than our knowledge of the historial distribution of periphyton communities.

Another anomaly in the output of the periphyton habitat suitability index is the distribution of high quality habitat for floating mat periphyton over most of WCA 2A under current hydrologic conditions. This accurately depicts observed mat development in portions of WCA 2A prior to eutrophication. However, eutrophication has eliminated periphyton mats from much of northern WCA 2A.

Summary

These relationships among groups of habitat suitability index models are of course based on the particular functions that were defined and how they were combined in any hydrologic simulation. These assumptions may change over time as new knowledge becomes available. In addition, new habitat suitability index functions may be added for other indicator species. Hence, the conclusions drawn above, while we believe to be accurate, are more intended to illustrate how information can be derived from such habitat

suitability index modeling exercises in leu of more detailed ecosystem monitoring and modeling.

While ecosystem habitat is not necessarily a measure of ecosystem response or condition, it is a reasonable approximation. The challenge, of course, is not only in defining habitat suitability functions that reasonably define those links between the water being managed and the relative ecosystem habitat response but also of combining, over time and/or over space, various habitat indicators for various ecological indicator species or landscape types.

CHAPTER 11

Conclusions

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The objective of this study was to demonstrate how ecological habitat suitability functions can be derived and linked to the hydrologic variables that are being managed. We desired a simple, transparent way to link ecology to hydrology, a way that would make it easy for anyone to understand, modify, test, and evaluate this linkage. Hydrologic targets and performance measures are commonly used to characterize the goals of the Everglades restoration effort. They are based on the assumption that if the hydrology can be managed so as to mimic what it was like prior to extensive management and drainage over the last century, the ecosystems may eventually return to natural, predrainage system conditions. It may or it may not return to this condition, but in any case it will be expensive. Along the way towards restoration it may turn out to be financially infeasible to continue – at least to the desired end. So, the questions are, "What if we do not get the water just right? What if we can get it only 90 percent right? What difference will it make? Is the added environmental benefit worth the added cost, assuming it is physically and politically possible? Where or how should limited financial resources be spent to get the greatest ecological benefit?" Questions like these require some link between hydrology and ecology.

The habitat suitability index models described in this document, although simplistic, provide trends and relative degrees of ecological response that allow comparisons of predrainage, current, and restored hydrologic conditions, at least with respect to the indicator features that were modeled. Different ecosystem indicators respond to these management-dependent hydrologic variables in different ways at different times and in different places or subregions of the Everglades. In this study, we chose six example indicators, some varying only over space, some only over time, and some over both space and time. The trophic levels included periphyton (algae), fish, alligators, and wading birds. Landscape features were the unique ridge and slough and tree island topographies that seems to be dependent on flow as well as depth variables, in spite of extremely low velocities through vegetation over a slope gradient that averages about 2 inches per mile.

The habitat suitability models presented in this document provide decision makers and planners with some additional insights about how the selected landscape features and faunal groupings have changed with the drainage and compartmentalization of the Everglades, and how and to what degree the restoration of more natural hydrologic

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conditions may translate to the restoration of desired ecological trends. Individual habitat suitability indices and the relationships among the groups of habitat suitability index models are of course based on the particular functions that were defined and how they were combined with hydrologic simulation output.

Where possible, the habitat suitability indices defined in this document were verified against field observation or best professional judgment. When applied to predrainage, current, and restored hydrologic simulations, habitat suitability index results showed, in some cases, room for improvement. Comparison among different habitat suitability indices helped quantify the relationship between different habitats interwoven within the Everglades mosaic. Anomalies in the balance between different habitat suitability indices indicated areas where further investigation of both the suitability index and our understanding of the inter-relationship between habitats and species, as well as our conceptualization of these relationships are needed. Sensitivity analyses showed the need for further refinement of the definition of some of the indices and also possible refinement of hydrologic model estimates of the predrainage conditions.

We lacked water quality modeling results, hence, our habitat suitability indices were functions of only water quantity variables. This assumes that there is a deterministic relationship between quality and quantity, and that this relationship is known. Neither is true, but until water quality models become operational, this together with perhaps some sensitivity analysis regarding the assumed qualities, is the best we can do.

Assumptions in the habitat suitability indices are expected to change over time as new knowledge becomes available and new habitat suitability index functions will likely be added for other indicator species. Hence, results and conclusions presented in this document, although accurate for the specified functions, are more intended to illustrate how such information can be derived and used in the absence of more detailed ecosystem modeling. While ecosystem habitat, quantified using habitat suitability indices, is not necessarily a measure of ecosystem response or condition, it is a reasonable approximation. Future challenges include not only defining habitat suitability functions that better represent those links between the water being managed and the relative ecosystem habitat response, but also learning how to best combine, over time and/or over space, various habitat indicators for different ecological indicator species or landscape types.

Obtaining an overall ecosystem habitat index could be considered mainly a scientific issue that requires the participation and best judgments of many different ecologists. If scientific consensus is not reached, then these relative measures of ecosystem condition will likely be less influential in the continuing political debate over how to manage South Florida’s water for not only the Everglades ecosystem but also for water supply, flood control, and recreation.

Managing water so as to satisfy, to the greatest extent possible given the financial resources available, all the interests of all those living in South Florida, together with all those not necessarily living in South Florida, who consider the Everglades ecosystem a national treasure, is more than just a scientific issue. Without some quantitative measures

of ecological conditions to trade-offs against quantitative measures of other water user interests, it becomes difficult to judge just what hydrology is ‘right.’ Clearly, it will depend in part on the money available to make it ‘right’ not only for restoring and preserving the Everglades but also for meeting the demands of the other water users in South Florida. Habitat suitability indices provide relative measures of these trade-offs with respect to the ecosystem. If water supply, flood control, and recreation are viewed as constraints, the essential trade-off is between cost and the relative overall measure of ecosystem habitat suitability.

An example of examining trade-offs was shown in our use of the habitat suitability indices to compare some water management alternatives and their impacts on various habitat indicators at different sites in the Everglades. Assuming our habitat suitability index functions for alligators are reasonable, we showed that the planned restoration flows with or without the planned ground water wells to be used for deep aquifer storage and recovery had no impact on alligator habitat in the Shark River Slough region. Removing the planned deep Lake Belt storage reservoirs, located along the East Coast, however, reduced the relative alligator habitat suitability in the same Shark River Slough region by about 20 percent. Elsewhere in the Everglades, the results could have been just the opposite. Habitat suitability indices provide a tool to examine where a particular restoration feature has the biggest benefit on a particular habitat or species, permitting better decision making on trade-offs over space with respect to that species. The decision process gets more complicated when more performance indicators are involved. Again, habitat suitability indices provide a way to examine potential trade-offs between impacts on different species and habitats, permitting informed decision making on alternative water management strategies.

To summarize, we have attempted to demonstrate a relatively quick, simple, and transparent way to consider the ecology of the Everglades prior to the accepted use of more complete ecosystem models. These include the Everglades Landscape Model (ELM) (www.sfwmd.gov/org/wrp/elm/) and the Across Trophic Landscape System Simulation (ATLSS) models (http://atlss.org/). From our experience in this project, we have concluded that involving a large number of experts to define and combine habitat suitability index functions greatly enhanced communication amongst scientists with differing opinions and increased our combined understanding of everyone’s views, concerns, and knowledge as we were forced to come to consensus to define each habitat suitability index. Defining, documenting, and producing these habitat suitability indices, as part of the automated hydrologic modeling postprocessing, links hydrology to ecology and permits the quick and easy quantification of the ecologic benefits of alternative water management strategies. This is an important milestone in the process of linking water management and hydrology with ecologic restoration. This first step needs to be followed by further examination and refinement of the existing habitat suitability indices, the development of new indices, and, of course, continued research and development of more detailed ecological models. The production of these habitat suitability indices has enhanced inter-disciplinary and inter-agency communication and provided a tool that can be used to increase our ecological and hydrologic understanding to benefit Everglades’ restoration.